HYBRID PROPULSION BASED ON FLUID-CONTROLLED SOLID GAS GENERATORS

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Abstract

The use of fuel-rich solid (gas generator-type) propellants for hybrid propulsion affords some design and utilization efficiency advantages. Both forward and aft liquid injection control concepts are evaluated from the operational standpoints of ballistics, throttling, stability and extinguishment. Steady-state and non-steady ballistics analyses are employed for this evaluation. Stability of solid motor operation is enhanced by fluid injection with adequate injector pressure drop. Efficient throttling and reliable extinguishment are attained through a combination of solid propellant combustion tailoring, grain design, control valves and sensors. Initial results from a laboratory-scale slab combustor, combining a gas generator propellant with gaseous oxygen injection, are also presented.

Nomenclature

a - coefficient in solid propellant burn rate law

A_b - solid propellant burn surface area

A_e - gas generator flow exit area (aft-injection concept)

A_t - nozzle throat area

c^* - characteristic velocity of combustion gases (subscript zero is for the fluid/solid mixture at the design point, subscript s is for the solid propellant alone)

F/S - fluid/solid ratio (subscript zero denotes the design point)

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g	gravitational constant
G_i	transfer functions (Fig. 21)
K_n	ratio propellant burn area/nozzle throat area (subscript zero denotes the design reference point)
K_{nG}	ratio propellant burn area/gas generator flow exit area (for the aft-injection concept)
$\dot{m}_f$	fluid injection flow rate
n	exponent in solid propellant burn rate law (pressure exponent)
n_f	effective pressure exponent with fluid-control
P	motor chamber pressure (subscript zero denotes design point)
P_c	thruster chamber pressure (aft-injection concept)
P_{DL}	pressure deflagration limit of propellant combustion
P_f	fluid injection feed pressure
P_G	gas generator pressure (aft-injection concept)
P_s	motor chamber pressure sustainable by the solid propellant alone in the absence of fluid injection
r	solid propellant burn rate (subscript zero denotes rate at the design point or reference pressure)
R	gas constant
s	Laplace transform variable
t	time
T	gas temperature (subscript s is for the solid propellant alone)
u_e	velocity of gases at gas generator exit (aft-injection concept)

V - combustion chamber free volume

δ - denotes perturbation quantity

ΔP - injector pressure drop

γ - ratio of specific heats of gas generator gases

ω - oscillatory frequency

ρ_e - density of gases at gas generator exit

ρ_s - solid propellant density

Θ_G - $[(RT_s/2g)(\gamma-1)/\gamma]^{1/2}$

τ_c - combustion chamber characteristic time

τ_f - feed system characteristic time (upstream of injector)

τ_s - solid propellant characteristic time

τ_Δ - injector characteristic time

Introduction

Hybrid propulsion is of interest for launch vehicle applications for reasons of safety, economy, environmental impact, controllability and performance potential.[1] The "pure" or "classic" hybrid employs an inert solid fuel in combination with a liquid oxidizer. An alternative approach under consideration is to replace the solid fuel with a fuel-rich gas generator-type solid propellant. Criteria for solid propellant selection are safety, economy, environmental impact, extinguishability and performance nearly equivalent to those of a solid fuel (so that it remains attractive on those bases) and, with ballistics properties and density more like a solid propellant, the approach should permit high propellant weight loading and utilization efficiency.

Lockheed Propulsion Company pioneered fluid-controlled solid R&D in the 1960s.[2] Many publications (reports, AIAA and CPIA papers) were generated that described various aspects of the technology (ignition, ballistics, combustion and specific impulse efficiencies, transient response and stability, throttling, propellant utilization, combustion extinguishment and re-ignition, motor design studies and a computerized model of duty cycles). Many types of injectants were used (oxidizers, fuels, inerts, gas generator gases), such that "mass augmentation" became another name for this concept. Other rocket companies also contributed to the R&D (most notably, Northrop Carolina and "Thiokol),[3] and the work continued into the early 1980s. One version of the concept has flown, and the largest solid rocket motor tested in this way contained about 550 kg of propellant (excluding the injectant).

Interest in the fluid-control concept for launch vehicles began in the mid-1980s. "The idea was to use some of the liquid hydrogen aboard a vehicle like the space shuttle to provide a modest throttling capability to the large solid rocket boosters. Subscale tests (7 kg propellant) were conducted at the Air Force Astronautics Laboratory (now the Phillips Laboratory).[4]

'The current version of the concept, proposed by Aerojet for future shuttle-type launch vehicles, consists of a gas generator-type solid propellant augmented by liquid oxygen.[5] However, the proposed design is not the more conventional injection into the forward end of the solid motor. Rather, the low temperature gas generator gases are piped to bipropellant injectors and then injected, together with the oxygen, into aft-end liquid rocket-type thrust chambers. A special injector design[6] incorporates a valve to meter the flow of the hot gases to maintain constant mixture ratio with the oxygen. Thrust termination is achieved by opening the valve to depressurize the gas generator while shutting off the oxygen flow.

A low energy solid propellant was selected to satisfy the above-stated requirements for this type of system. The aft-injection scheme was chosen as a way to maximize propellant utilization and combustion efficiency. However, it requires more complexity in the feed, control and injection systems, the additional thrust chambers, and a heavier motor case because the gas generator has to operate at a sufficiently high pressure to assure a stable and efficient feed to the thruster chambers.

It is not clear that an aft-injection scheme is necessary to maintain combustion efficiency and mixture ratio. 'The concern about efficiency came from experience with pure hybrids, where some type of mixing enhancement aft of the solid fuel grain proved to be necessary. However, the fluid-controlled solid propellant operates by a different combustion mechanism and does not require the same type of mixing. Lockheed tested a series of 5 kg motors using chlorine trifluoride as the injectant through a simple head-end injector. Even at this scale, the measured specific impulse efficiencies were in the 90s.[7] While the aft-injection concept is a clever way to maintain constant mixture ratio, it is not without problems of its own and the added complexities may not be required.

The purpose of this paper is to evaluate the operational characteristics of both forward-injection and aft-injection versions. Initial results from a laboratory-scale slab combustor, combining an Aerojet gas generator propellant formulation with gaseous oxygen, will also be presented.

General Description

The fluid-controlled solid concepts are illustrated schematically in Fig. 1. An advantage of the aft-injection concept is that the solid motor operates at a much lower temperature, about 1400°K, compared to temperatures ca. 3500°K. With aft-injection, the high temperature is limited to the aft thrust chambers which are regeneratively cooled by the oxygen flow.

For either concept, ignition can be accomplished by a pyrogen charge or a bipropellant igniter. With forward-injection, throttling and extinguishment are achieved with the liquid control valve. For this aft-injection concept, they require a coordinated effort between troth liquid and gas generator control valves. Extinguishment results from depressurization of the solid motor to the environmental pressure, below the deflagration limit of the propellant.

Performance is illustrated by the curve of characteristic velocity vs. fluid/solid ratio, shown in Fig. 2. The peak specific impulse is comparable to a pure hybrid[5] and is achieved at a much lower fluid/solid ratio, which offers packaging advantages. Even though there is more weight of solid propellant for a given total impulse, its higher density and improved volumetric loading result in a reduction of about 40% in the size of the solid motor that would be needed for the pure hybrid. The amount of liquid oxygen required is reduced by about 1/3, because of the lower fluid/solid ratio. Thus the fluid-controlled solid propulsion system is considerably smaller in size than an equivalent pure hybrid.

Analysis of Forward-Injection

Principle of Operation

The basic principle of operation of the fluid-controlled solid motor is illustrated in Fig. 3. There is a different nuance

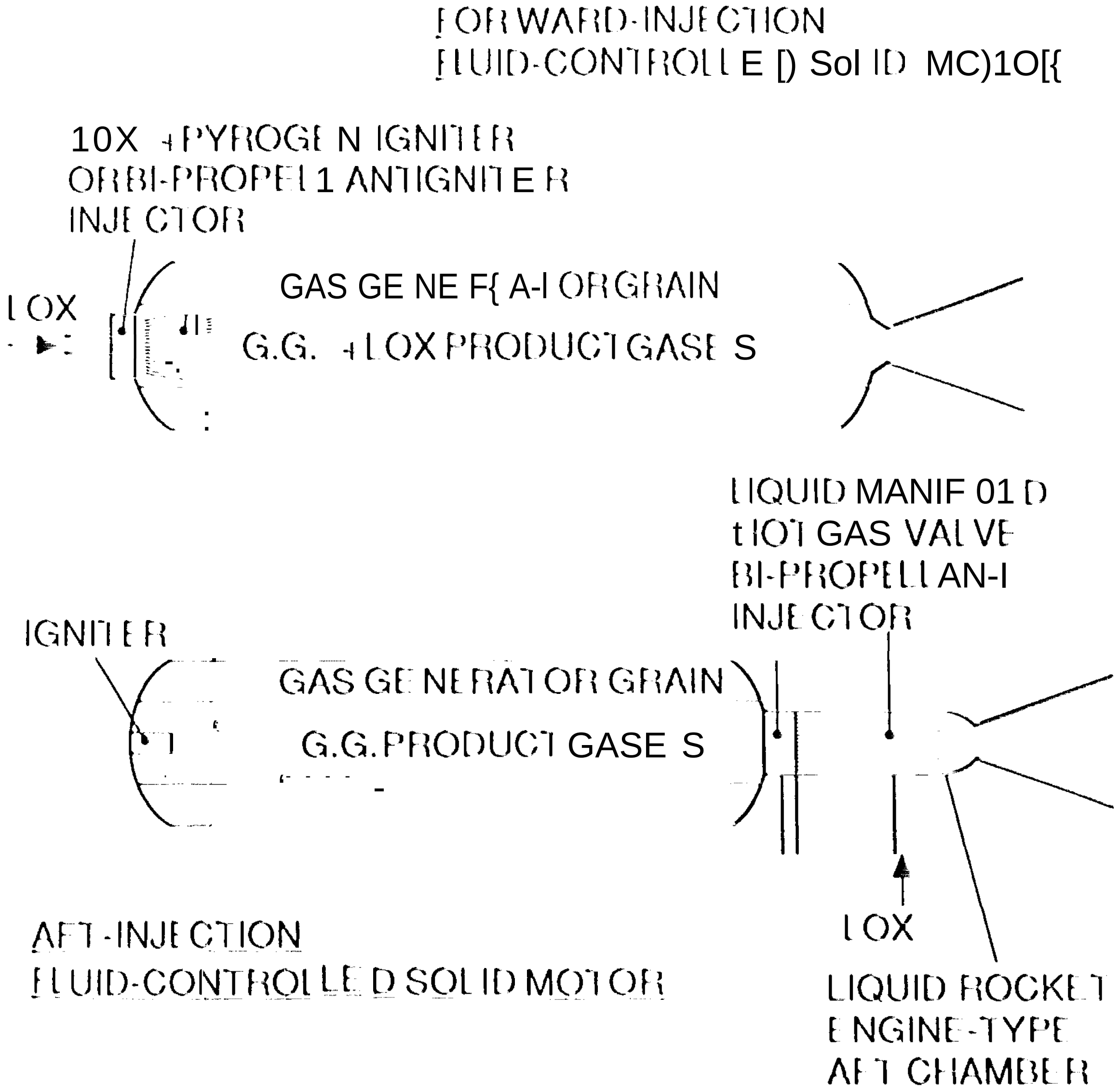

FIG. 1 Schematic illustration of alternative hybrid propulsion concepts

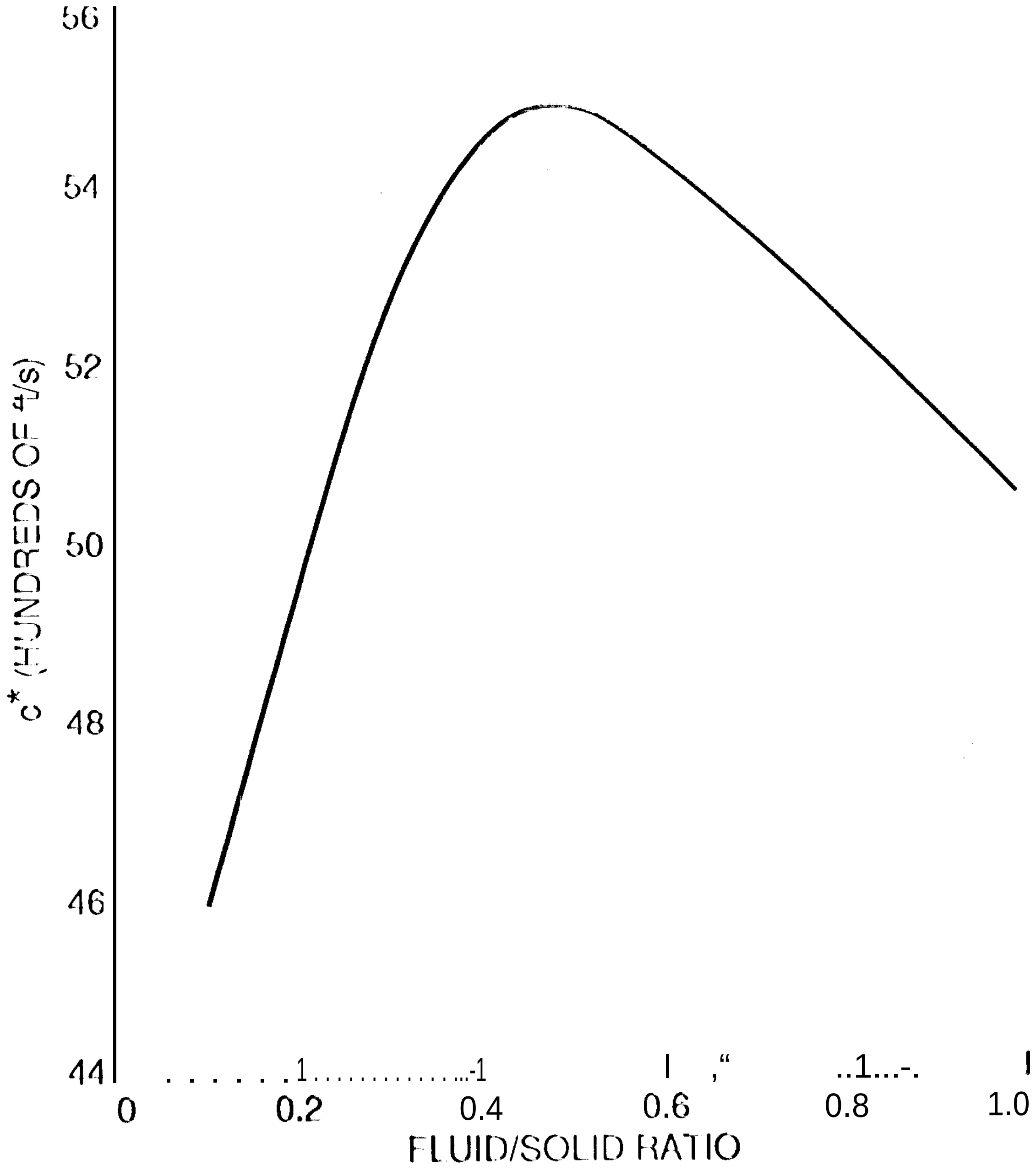

Fig. 2 Characteristic velocity of LOX plus solid gas generator propellant combination

with the aft-injection concept, which will be covered later under its heading. Figure 3 contains plots of solid propellant mass influx vs. pressure with pressure exponent as a parameter, and total (solid plus liquid) mass efflux through the nozzle. Mass flux is mass flow rate per unit of burn surface area. Equilibrium pressure is achieved where total mass influx equals total efflux. The mass influx lines were drawn to converge at the selected design point pressure, to show the parametric effect of pressure exponent. It is observed that the liquid injection serves to make up the mass influx deficiency from the solid alone, to achieve the design pressure for that value of K_n corresponding to the mass efflux line. The procedure is to select a fluid/solid ratio for that design pressure, 0.5 in this case, and that determines the value of K_n required. Mathematically,

$$\dot{m}_f + \rho_s A_b r = gPA_t/c^* \qquad (1)$$

and with the standard burning rate law, Eq. (1) can be written as:

$$F/S + 1 = gP_0(P/P_0)^{1-n}/(c^* \rho_s r_0 K_n) \qquad (2)$$

which becomes, at the reference (design) point:

$$(F/S)_0 + 1 = gP_0/(c_0^* \rho_s r_0 K_{n0}) \qquad (3)$$

This equation is illustrated by the example of Fig. 4. The required K_n is shown as a function of the selected fluid/solid ratio, using Fig. 2 and the other properties of a reference gas generator propellant, for a pressure of 6.2 MPa (the nominal initial pressure of the SRM solid rocket booster),

If on-command shut-down is required, an additional consideration enters into the design procedure.

It is recognized that pressure exponent is not a constant over a wide pressure range. There often is an increase in exponent at low pressures and as the low pressure deflagration limit is approached. This is represented in Fig. 3 by a shift to an exponent of 1 below certain pressures, and deflagration limits are also represented, Higher exponent propellants tend to exhibit combustion limits at higher pressures, the mechanism being more like a minimum burn rate to satisfy a stable energy balance in the combustion zone.

It is observed from Fig. 3 that higher exponents and higher pressure deflagration limits are desirable properties for this concept. If the exponent is too low, the solid will be able to sustain a lower equilibrium pressure all by itself when

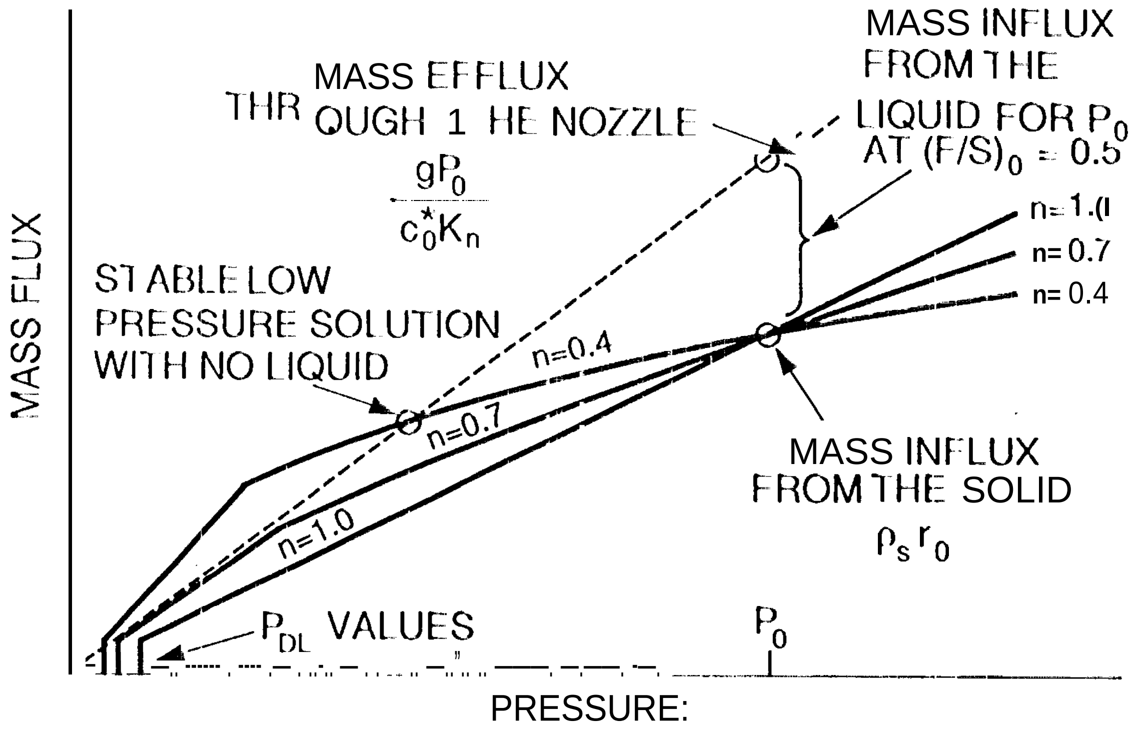

Fig. 3 Ballistic design of fluid-controlled solid motor

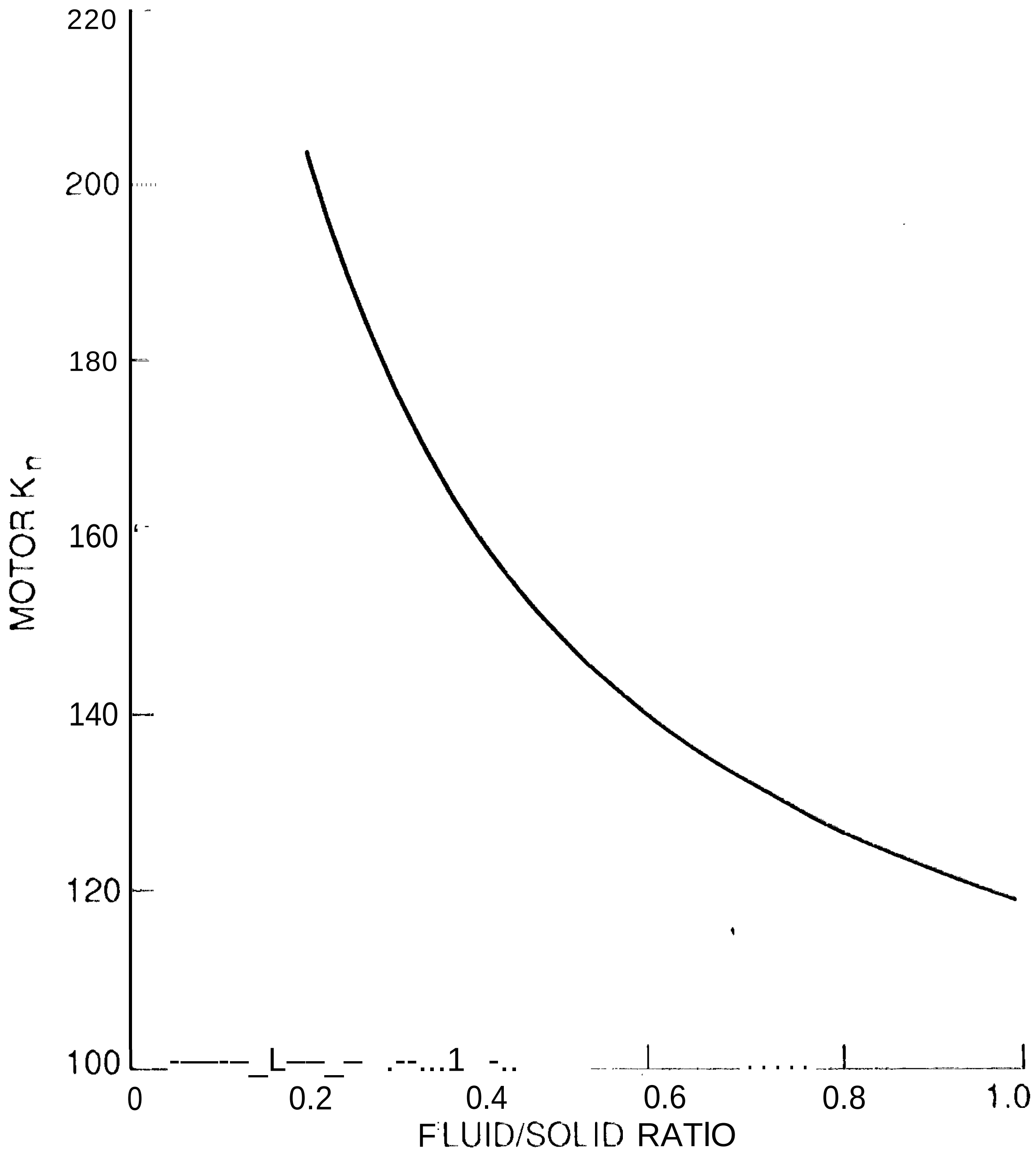

Fig. 4 Motor K_n corresponding to selected fluid/solid ratio to achieve 6.2 MPa pressure with LOX plus solid gas generator combination

the liquid is shut off. This is depicted by the solution with n = 0.4. The way around this would be to either increase the F/S ratio at the design point, requiring a smaller K_n, or to reduce the design pressure for the same F/S ratio, also requiring a smaller K_n. Both changes are probably undesirable, but the aim is to achieve a K_n value small enough to enable the mass efflux line to clear the bulge in the mass influx line so that the pressure can fall all the way down to ambient. With n = 0.7, this desired result is barely achieved from the design condition. With n = 1, this result is easily achieved, and a lower F/S ratio could be selected if desired. For a constant exponent less than 1, an equation for the low pressure solution (for the solid alone) can be derived as:

$$(F/S)_0 + 1 = (P_0/P_s)^{1-n} c_s^* / c_0^* \quad (4)$$

which accounts for the difference in c* between fluid control and the solid alone. But the graphical solution procedure (Fig. 3) helps to illustrate these points and achieve a conservative design.

The stability concerns in using high exponent propellants will be addressed subsequently. It turns out that fluid control has a strong stabilizing effect. Again, there are different nuances on this point with the aft-injection concept.

Stability. with High Exponent Propellants

Taking the liquid injection flow rate as proportional to the square root of injector pressure drop, differentiating Eq. (1) with respect to burn area (a variable of concern because of possible abnormalities as well as normal burn patterns), and normalizing with respect to the mean pressure, the static stability of the motor can be expressed as:

$$d(\ln P)/d(\ln A_b) = 1/[1-n+F/S(P_f/P-1/2)/(P_f/P-1)] = 1/(1-n_E) \quad (5)$$

Note that, with F/S = O, the equation reduces to the familiar form for solid rocket motors whence a high exponent is destabilizing and n = 1 is impermissible. A disturbance to the burn area would result in a runaway pressure. However, with F/S > 0, the stability improves. The result is shown graphically in Fig. 5.

The denominator of Eq. (5) can be expressed in terms of an "effective exponent", combining its last 2 terms to show a decrement to n. Fig. 5 shows this effective exponent plotted vs. F/S, for a propellant with n = 1, and with the injector pressure ratio as a parameter. The limit of infinity corresponds to an infinite feed pressure or constant fluid

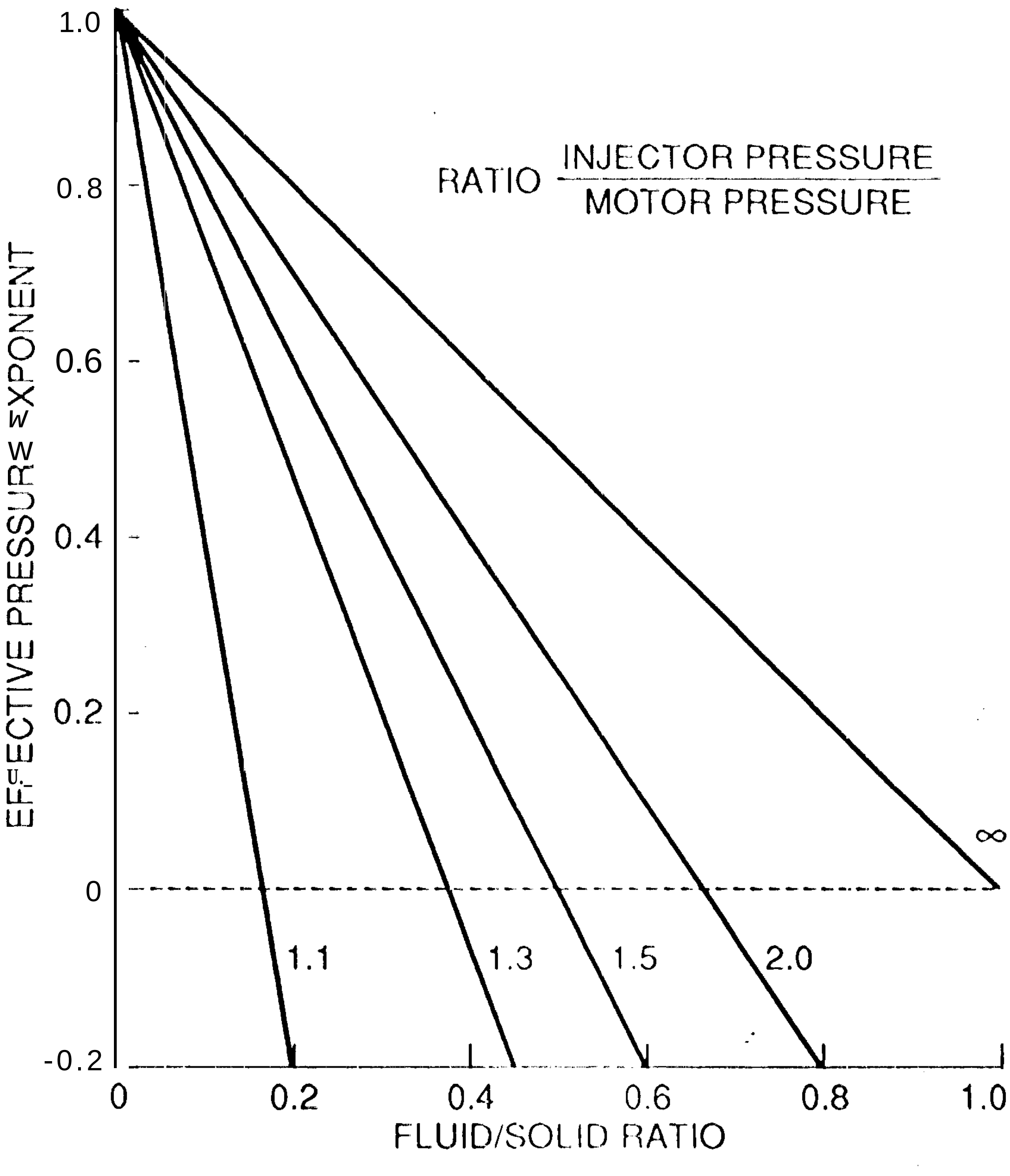

Fig. 5 Effective pressure exponent of $n = 1$ solid propellant with fluid control

injection rate. It is observed that with F/S = 0.4, and an injector pressure ratio of 1.3 (the ratio must be adequate to assure a stable and efficient feed), the effective exponent becomes -0.07. Thus the motor is as if it contained a plateau propellant, a very desirable property, With F/S = 0,5, it becomes like a mesa propellant (exponent is more negative), which is a most desirable property.

Lockheed Propulsion developed and successfully tested n = 1 propellants with fluid control,[7,8] Not only was the static stability demonstrated, but dynamic stability improvements expectable from reductions in effective exponent were also apparent, There has never been an instance of acoustic combustion instability with fluid control, even though most of the tests were with non-aluminized propellants, In tests at very low pressures, to explore deep throttling and extinguishment properties, instances of L* instability showed that fluid control stabilized this dynamic characteristic,[9,10] With increased F/S ratio, the L* stability boundary was shifted to lower values of L" and pressure. Thus the successful use of high exponent propellants with fluid control has been well demonstrated,

One other dynamic characteristic that merits discussion is the stability of the fluid feed system. This can be expressed in terms of a minimum injector pressure drop required, It is affected by pressure exponent because disturbances in the feed can couple with the dynamics of propellant burn rata through the fluctuations in chamber pressure. The feed system stability can be derived from the response of chamber pressure to a fluctuation in the injector pressure drop, A perturbation analysis yields the following expression:

$$\frac{\delta P}{\delta(P_F-P)} = \frac{\exp(-s\tau_P)}{2\left(\frac{1+F/S}{F/S}\right)\left(\frac{\Delta P}{P}\right)(1+s\tau_\Delta)\left(1+ \text{“}C - \frac{n\exp(-s\tau_s)}{1+F/S}\right)} \qquad (6)$$

where the various τ are characteristic (relaxation) times of the components (see Nomenclature) and s is the Laplace transform variable. For a sine wave disturbance, s = $i\omega$ would be used to evaluate the stability, A sufficient condition for stability is that the steady-state response be equal to or less than the input disturbance. This is conservative, because a phase lag between the response and the disturbance would allow a gain greater than unity. However, it simplifies the analysis by eliminating the components (nothing is being designed at present, anyway) and the complex variables. The steady-state response is obtained with $s = 0$, whence the stability criterion becomes:

$$\Delta P/P \geq F/S/[2(1 + F/S - n)] \tag{7}$$

Eq.(7) is shown plotted in Fig. 6. It is observed that the required injector pressure drop increases with exponent and with fluid/solid ratio. For n = 1, the pressure drop should be half of the chamber pressure regardless of fluid/solid ratio. However, experience with fluid-controlled motors has shown that a smaller pressure drop can be tolerated without instability, confirming that Fig. 6 is conservative, The essential points are that there need be no concern about using high exponent propellants for fluid-controlled motors, and that feed system stability should be addressed by analysis and testing in the course of developing a design.

Throttling and Propellant Utilization

Dividing Eq. (2) by Eq. (3) yields an expression for fluid/solid ratio excursions that would occur by reducing fluid injection rate to reduce pressure:

$$(F/S + 1)/[(F/S)_0 + 1] = (K_{n0}/K_n)(c_0{}^*/c^*)(P/P_0)^{1-n} \tag{8}$$

For n = 1 and constant K_n (neutral grain design), it is readily apparent that fluid/solid ratio becomes independent of pressure, so there is no utilization problem in throttling. This is another advantage of higher exponent, and is illustrated in Fig, 7. The pressure variation corresponds to that of the SRM solid booster. For n = 0.6, there is a large excursion in fluid/solid ratio over this pressure range.

In reality, grain designs are not perfectly neutral even when intended to be neutral, and non-neutral geometries may be desirable for certain purposes, Fig. 8 shows the effect of a 15°A reduction in K_n from the nominal design point, computed from Eq. (8) and using Fig. 2. A large increase in F/S is required to restore the initial pressure (obtained by throttling up), and with n = 1 the effect of the K_n change is to imbalance the utilization (from the nominal F/S = 0.5) regardless of the pressure. With lower exponents, the F/S excursions with pressure move toward restoring the balance

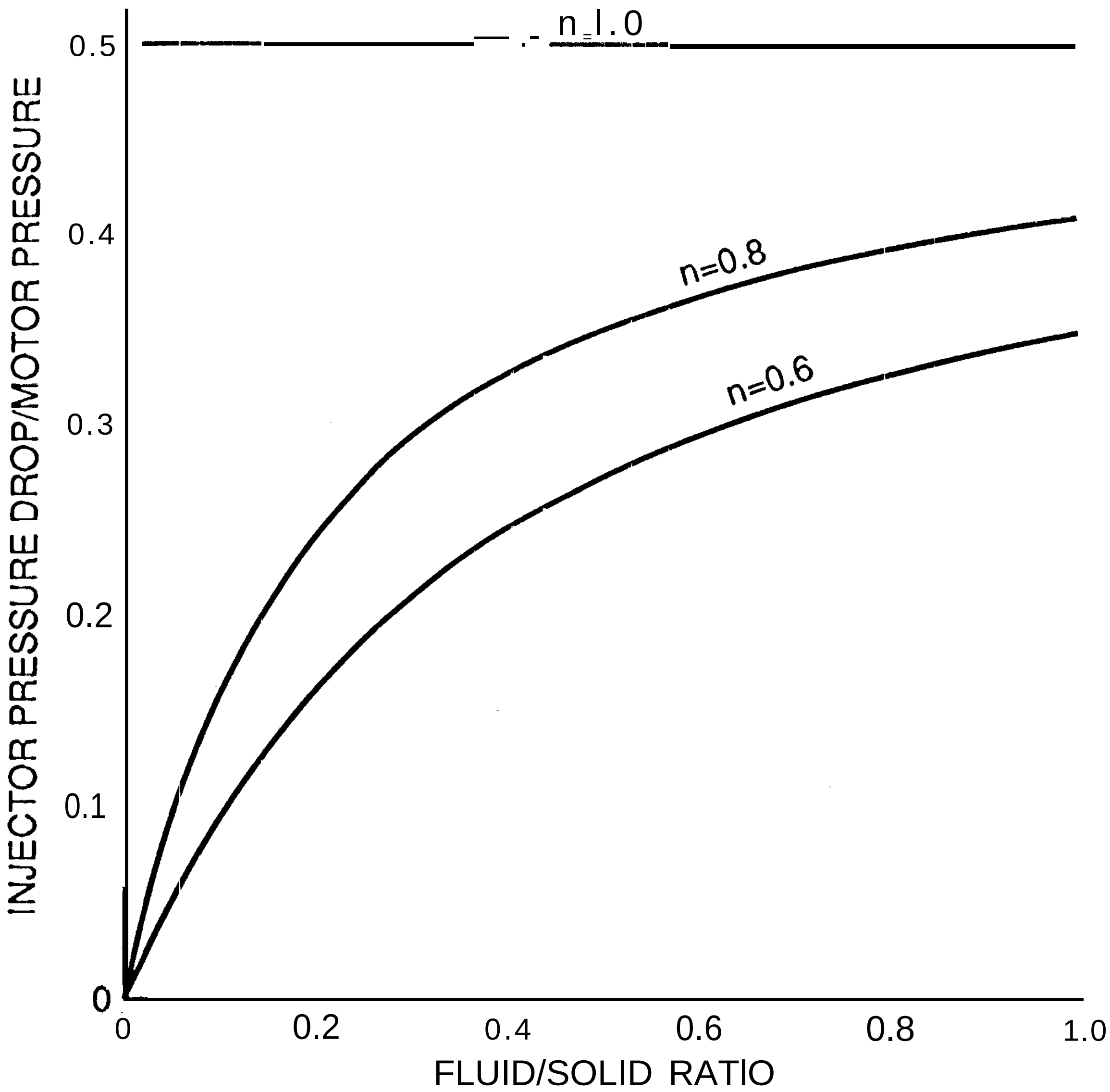

Fig. 6 Conservative estimate of injector pressure drop required for feed system stability

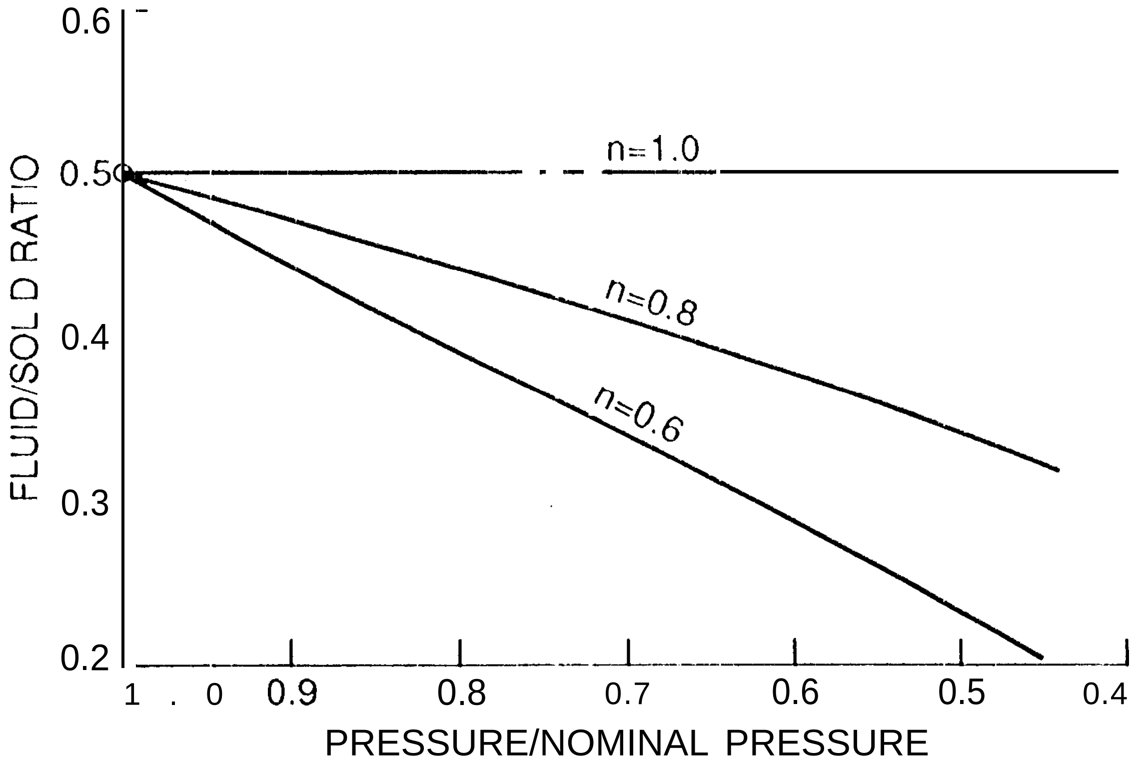

Fig. 7 Fluid/solid ratio excursions in throttling with neutral grain design

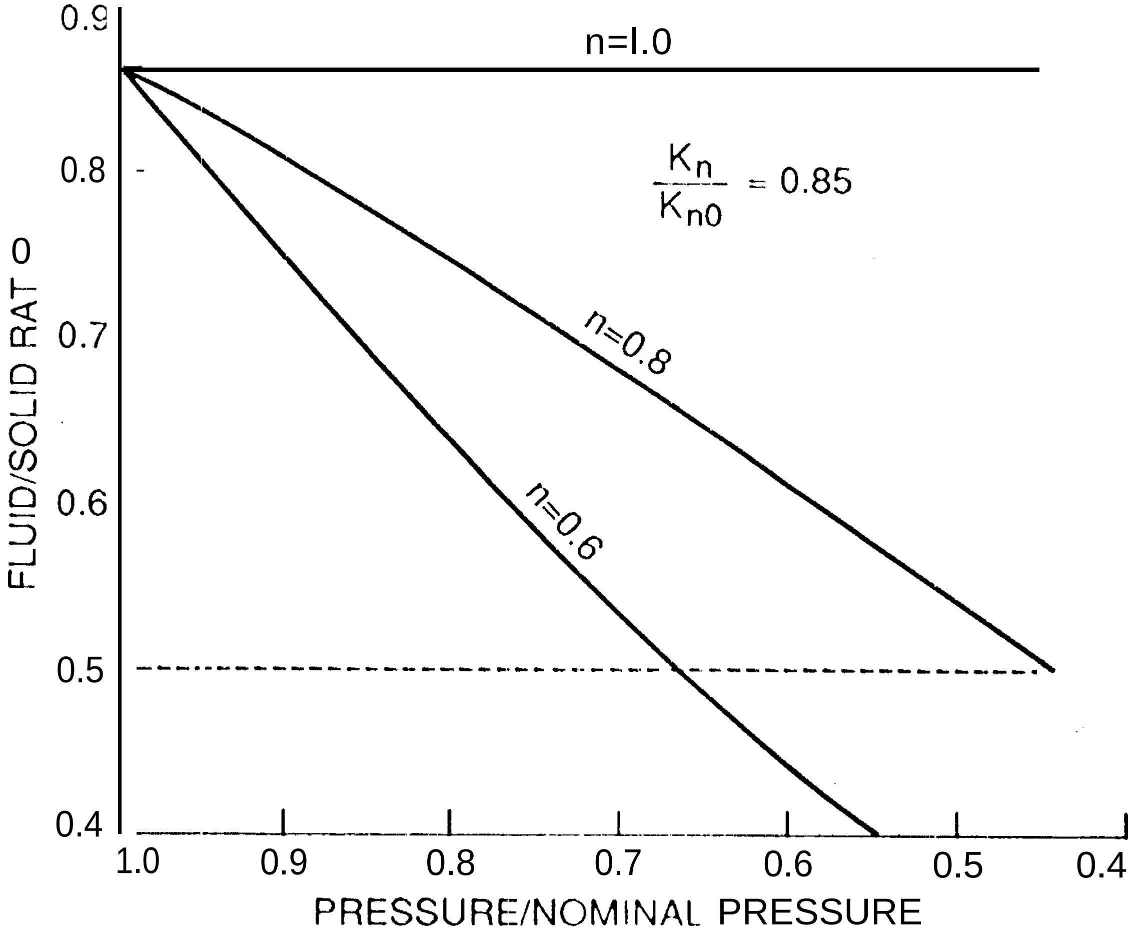

Fig. 8 Effect of Q reduction in burn area on fluid/solid ratio for same pressure schedule as Fig. 7

in the course of the firing, l-bus the realities of grain design and system variances temper the ideality of $n = 1$.

The SRM solid booster achieves its “throttling” by grain design, which produces about a 40% reduction in K_n. A more modest regressivity combined with an exponent slightly less than 1 could achieve the same degree of throttling with a constant fluid/solid ratio. Fig. 9 shows a program of a pressure schedule vs. the K_n schedule of the grain design to achieve a constant F/S = 0.5 with n = 0.8, Only a 15% reduction in K_n is required, the rest of the throttling being accomplished by the liquid flow schedule. If there were no variances, this program would set the liquid flow schedule. The thrust profile requirement would set the functions of time (and thus the specific grain design),

The major source of motor-to-motor variance is the nominal propellant burn rate, due to batch variations and propellant temperature. This could be accommodated by a system of on-board sensors coupled with softwear that would rationalize a ballistic deviation and adjust the liquid flow schedule to maintain the constant F/S. The greater the departure from a neutral grain and/or the greater the expected variance, the more desirable it is to have $n < 1$ to keep a constant F/S while accommodating these changes. On the other hand, the smaller these changes, the closer the ideal of $n = 1$ can be approached. The effect of accommodating the variance would be a motor-to-motor variance in the thrust profile similar to conventional solid motors. The desirability of using fluid control to maintain an exact thrust profile (or exact ascent requirement) vs. full propellant utilization (a constant F/S) would be a matter for trade-off study in an application.

Thrust Termination Transients

Assuming instantaneous cut-off of the liquid injection (injector face shutoff), a closed form solution for the pressure decay in the motor can be derived from the following mass balance differential equation:

$$(V/RT)dP/dt = \rho_s A_b a P^n - gPA_t/c^* \quad (9)$$

which becomes, after normalizing by the initial pressure:

$$d(P/P_0)/d(t/\tau_c) = (P/P_0)^n/[1 + (F/S)_0] - P/P_o \quad (lo)$$

For the special case of n = 1, integration yields:

$$P/P. = \exp[-(F/S)_0/[1 + (F/S)_0] \cdot t/\tau_c] \quad (11)$$

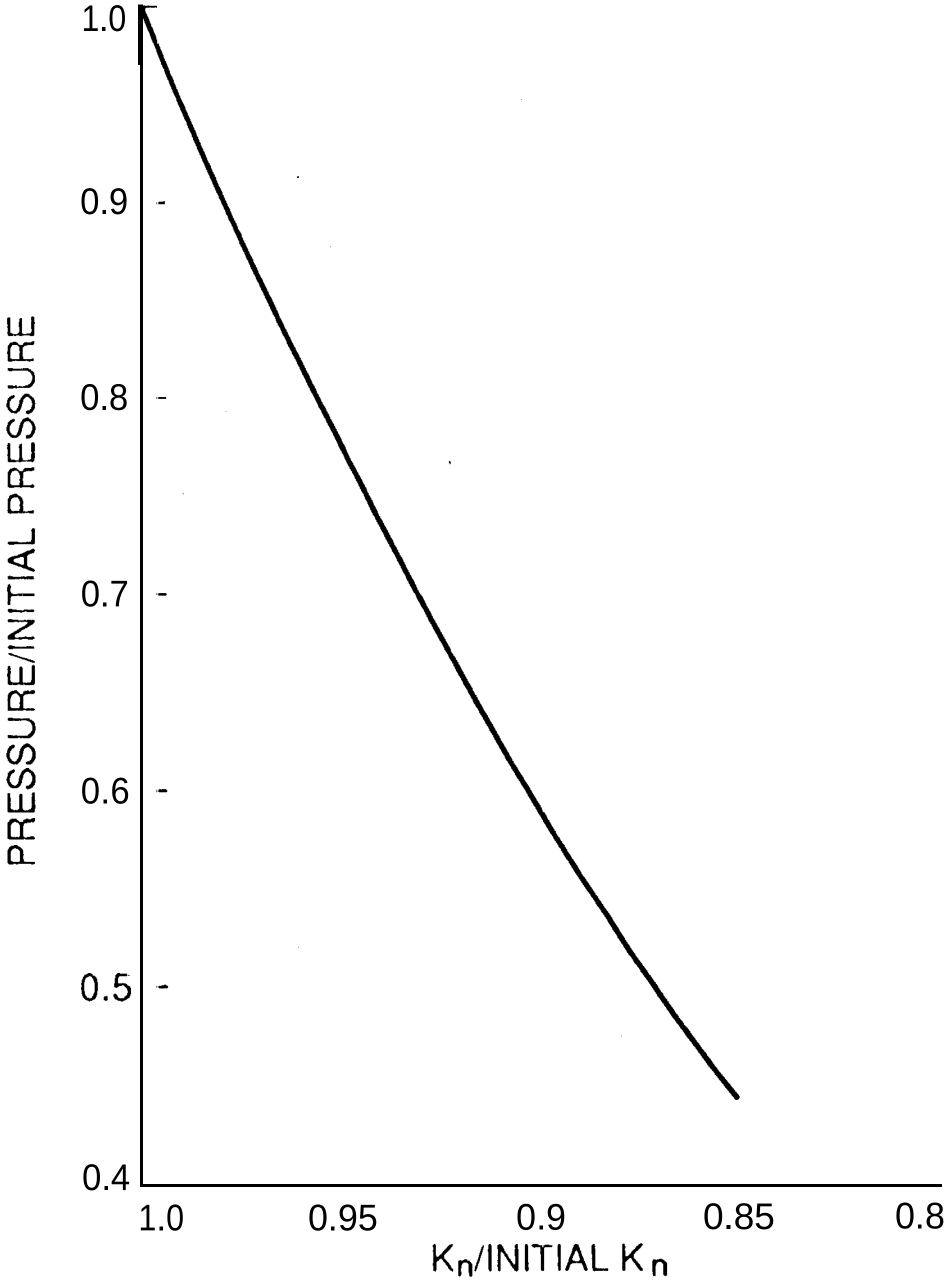

Fig. 9 Tailored grain design to maintain constant fluid/solid ratio (F/S = 0.5) for Fig. 7 pressure schedule with n = 0.8

and for n < '1:

$$P/P_o = \{[1 + (F/S)_0 \exp(-[1 - n]t/\tau_C)]/[1 + (F/S)_0]\}^{1/(1-n)} \quad (12)$$

Results with pressure exponent as a parameter are shown in Fig. 10 (for F/S = 0.5), and with fluid/solid ratio as a parameter in Fig. 11 (for n = 1). The analysis is inexact because low pressure combustion and gas temperature variations are not accounted for. Those details would accelerate the pressure decays. The point is to show relative benefits of higher exponent and higher F/S ratio in promoting faster pressure decays. With higher exponent, burn rate falls more rapidly with the decreasing pressure. With higher F/S, a larger percentage of the total mass input is shut off; actually, it is better than illustrated because the value of τ_c decreases with increasing F/S (motor L" decreases with increasing F/S), so on a dimensional time basis the curves would be further apart.

Analysis of Aft-Injection Concept

Principle of Operation

The basic principle is the same as with forward-injection, but there are differences in detail because of the separate combustion chambers. The orifice that controls the pressure in the thrust chamber (the nozzle throat) is no longer the same as that which controls the pressure in the solid motor (the hot gas valve), The solid gas generator motor has to operate at a higher pressure than that required for thrust from the liquid engine-type thrust chamber.

The analogy to Fig. 3 for the aft-injection concept is shown in Fig. 12, which reflects the differences. The abscissa is now the gas generator pressure, not the thrust-producing chamber pressure. It is assumed that the gas generator has to operate at a nominally 25% higher pressure than the thrust chamber for a stable and efficient feed of the gases through whatever ducting to the bipropellant injector. This is reflected on Fig. 12 by positioning the gas generator pressure at a 25°A higher value than on Fig 3. Gas generator mass influx lines are shown for 2 values of pressure exponent; n == 1 is not shown because of the possibility that the gas generator could become isolated from the fluid control (the gas generator is nominally unchoked, so there is a coupling, but prudence would avoid n = 1 in this case).

Since the abscissa is gas generator pressure, and the rocket nozzle controls chamber pressure, mass efflux through

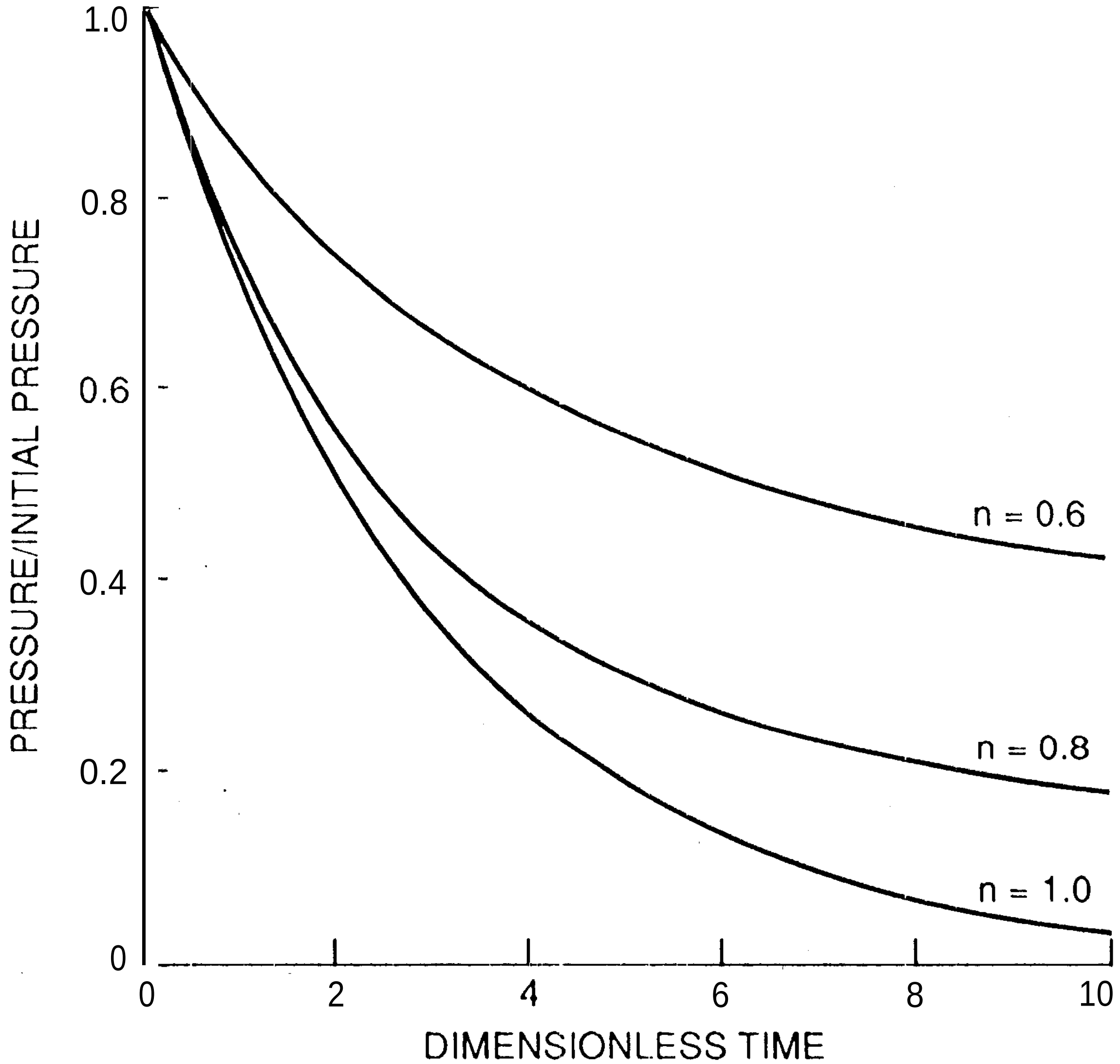

Fig. 10 Effect of pressure exponent on pressure decay following liquid cut-off, with $(F/S)_0 = 0.5$

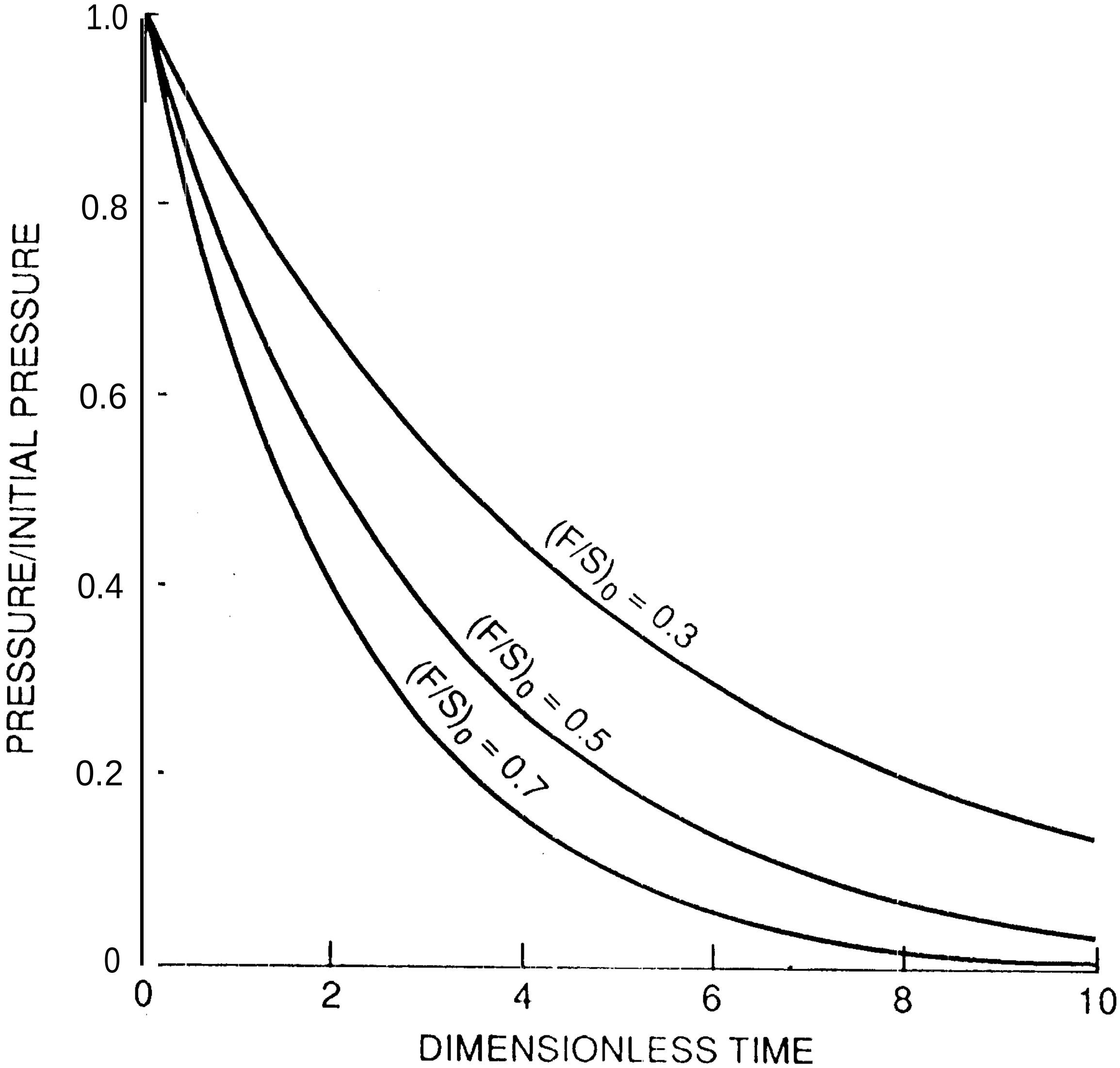

Fig. 11 Effect of fluid/solid ratio on pressure decay following liquid cut-off, with n = 1.0

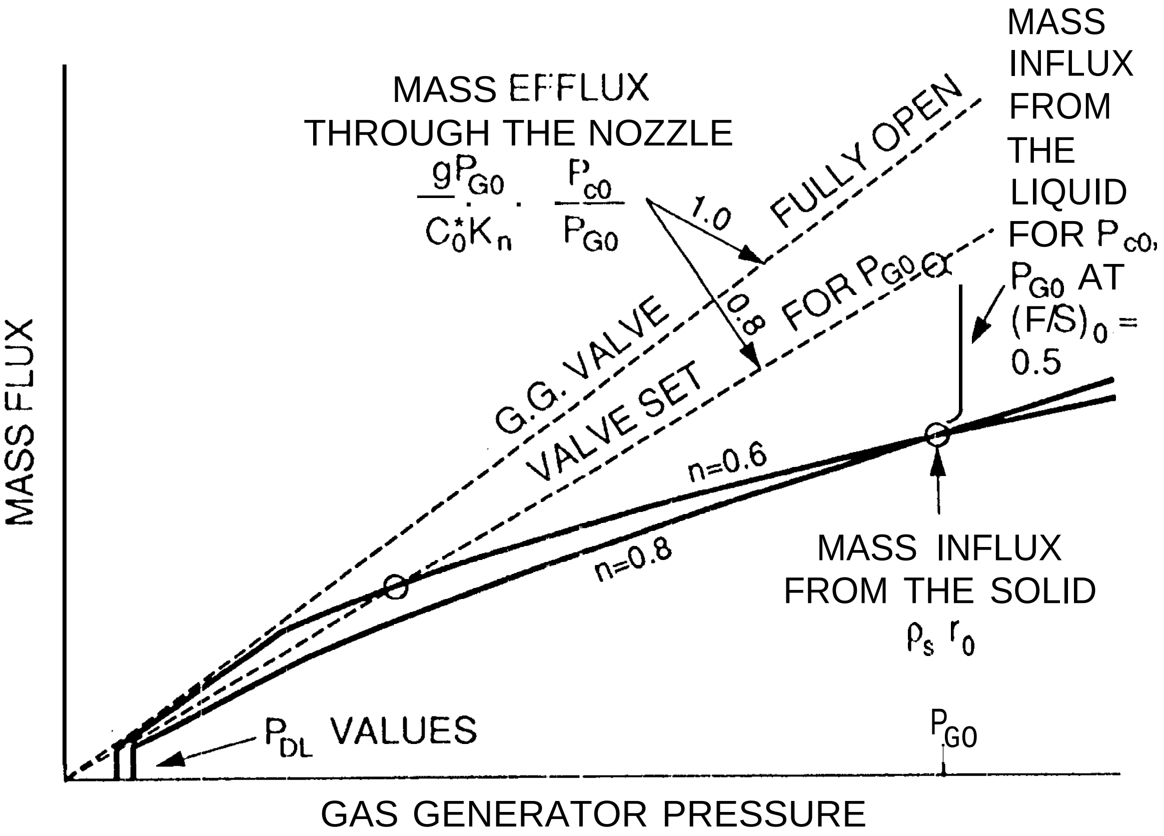

Fig. 12 Ballistic design of hybrid motor using aft-injection concept

the nozzle shown on Fig. 12 will vary with the pressure ratio. Two mass efflux lines are shown. One corresponds to the nominal design point, with F/S = 0.5 and a pressure ratio of 1,25. Note that, with no change in valve position, the gas generator would sustain a low pressure by itself upon liquid shut off if n = 0.6. The second mass efflux line corresponds to opening the gas valve to equalize the two chamber pressures. By opening the valve it is possible to clear the mass influx line for n = 0.6 and achieve the desired repressurization upon liquid shut off. This condition is more easily met with n = 0.8. Of course, the nozzle throat places a limit on how much the gas generator can be depressurized by opening the valve. This limit could be circumvented by providing additional overboard dumping capability to the gas generator.

Mathematically, ballistic solutions are obtained by coupling the mass balance equations for the two chambers. Using the conventional burn rate law, the unchoked gas generator pressure is given by:

$$\rho_s A_b a P_G^n = \rho_e u_e A_e \tag{13}$$

and the thruster chamber pressure is given by:

$$m, + \rho_s A_b a P_G^n = g P_c A_t / c^* \tag{14}$$

Using the unchoked boundary condition, equation of state and isentropic law for the gas generator gas, the simultaneous equations become:

$$\rho_s r_0 K_{nG} (P_G/P_{G0})^n \theta_G = P_c [(P_G/P_c)^{2(\gamma-1)/\gamma} - (P_G/P_c)^{(\gamma-1)/\gamma}]^{1/2} \tag{15}$$

$$PC = (1 + F/S)(P_G/P_{G0})^n \rho_s r_0 K_n c^* /9 \tag{16}$$

Eq. (16) shows that Fig. 4 also applies to the aft-injection concept for the thrust chamber pressure at the nominal design point, After selecting F/S, which determines K_n for that pressure, the selected pressure ratio then determines the valve control area from Eq. (15). The ability to repressurize the gas generator to ambient by opening the valve with F/S = O can then be assessed from these equations. Changes in the pressure exponent and thermochemistry of the gas generator propellant at low pressures should be accounted for in this analysis (as with Eq. (6) or the graphical procedure for forward-injection).

Throttling and Propellant Utilization

If throttling were accomplished merely by reducing the liquid flow rate to the thrust chamber, doing nothing with the gas generator control valve, results are shown in Fig. 13 (for two values of n). The gas generator pressure would fall (solid lines), and the fluid/solid ratio would shift to lower values (dashed lines), The higher exponent produces a smaller excursion in F/S because it enables the gas generator pressure to fall a greater amount, to be more in keeping with the reduced liquid flow.

Eqs. ('15) and (16) can be combined to show a control valve schedule that maintains a constant fluid/solid ratio in throttling, The combination yields:

$$[(A_t/A_e)(g\theta_G/c^*)/(1+F/S)]^2 = (P_G/P_c)^{2(\gamma-1)/\gamma} - (P_G/P_c)^{(\gamma-1)/\gamma} \tag{17}$$

Eq. (1 "7) is shown plotted in Fig. 14 for three values of F/S held constant. As chamber pressure falls due to the reduced liquid flow, the valve is adjusted to maintain the pressure ratio required to hold the constant value of F/S. With a neutral grain, this requires opening the valve, moving to the left on Fig. 14, dropping the pressure ratio. The gas generator pressure is able to fall a greater amount than was the case in Fig. 13.

An example of this full-utilization throttling is given in Fig, 15, The F/S is being held constant at 0.5 with a neutral grain design, Shown plotted are the changes in gas generator pressure (solid lines) and control valve area (dotted) curves). At several points, the pressure ratios then existing are indicated, The low values of pressure ratio being reached, especially with n = 0,6, are cause for concern. Calculations were stopped where the pressure ratio reached 1,02 (also noted with an x). With n = 0.8, the throttling schedule of the SRM solid booster was barely met. It is likely that the pressure ratio will be limited to higher values in a real system.

An approach to maintain adequate pressure ratio is to use a regressive grain design, analogous to the approach discussed for forward-injection. Fig. 16 shows two schedules of K_n reductions associated with the SRM booster throttling range, one for each value of exponent. The criteria determining these schedules were to have the same gas generator pressure change with either exponent, and to maintain the constant F/S by increasing the pressure ratio as the pressure falls, but without choking the gas generator, This is a reasonable course to follow to assure a stable and

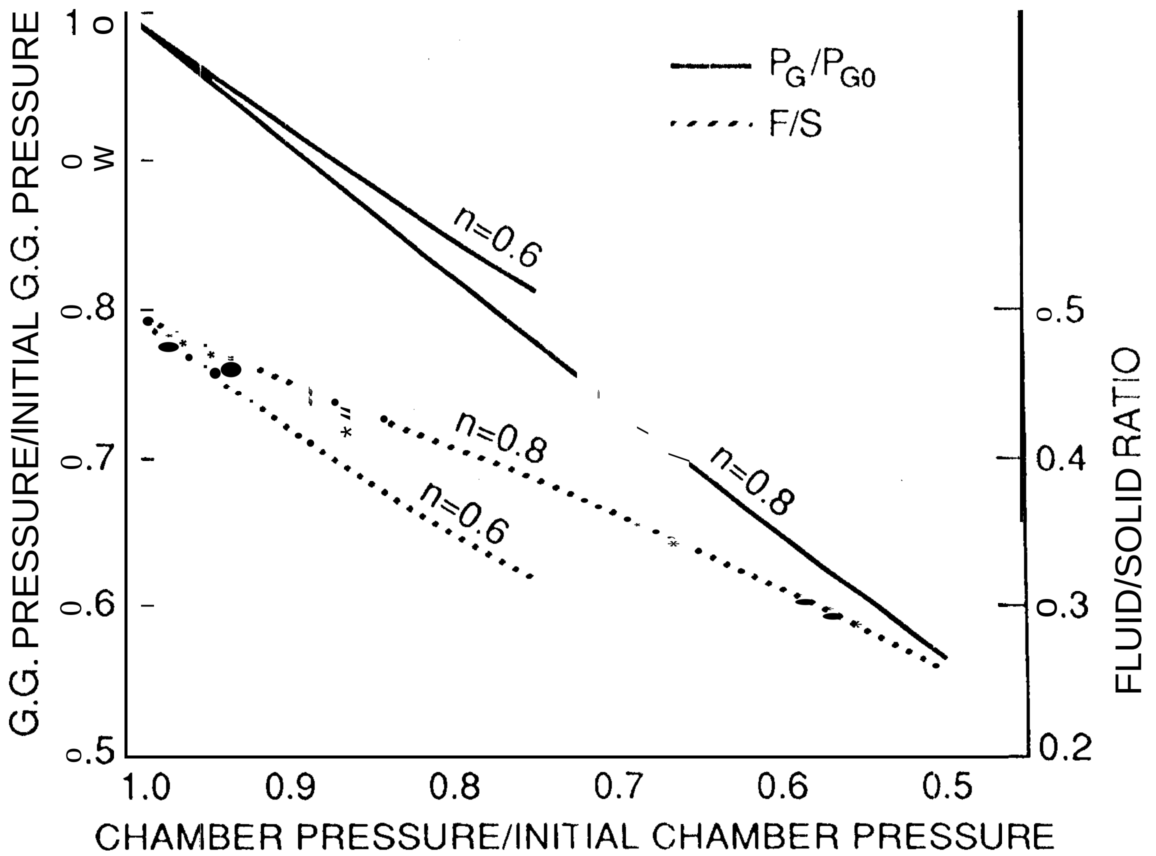

Fig. 13 Effect of throttling via liquid injection only on gas generator pressure and fluid/solid ratio (fixed valve position, neutral grain design)

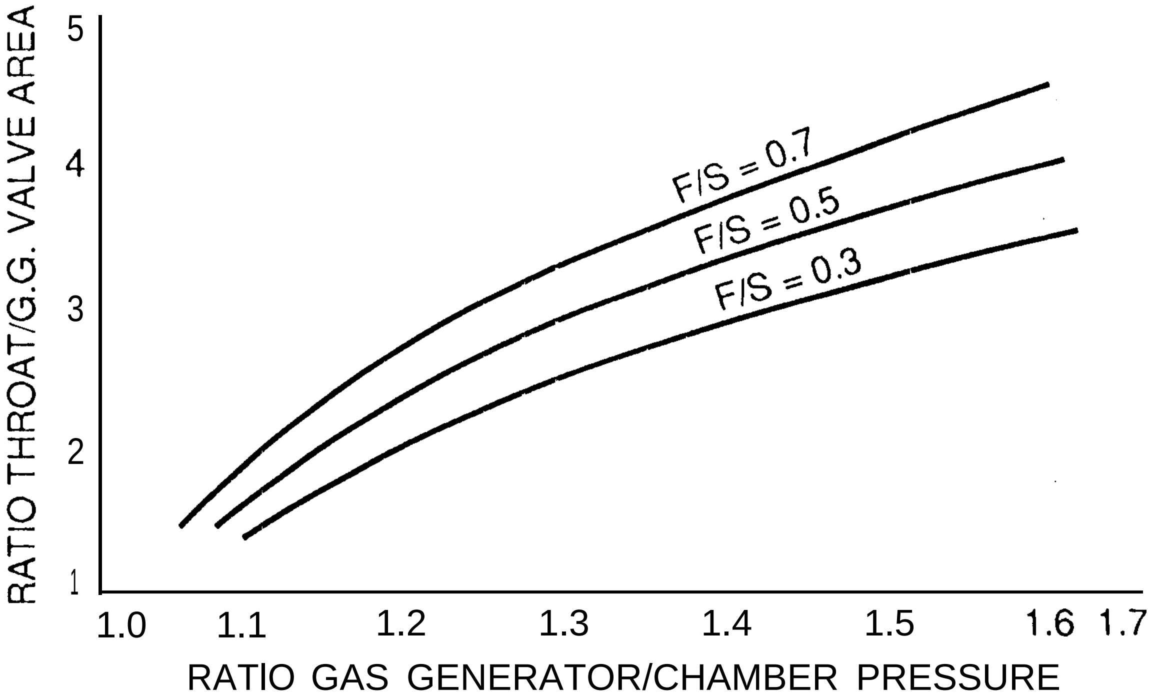

Fig. 14 Gas generator control valve schedules to maintain constant fluid/solid ratio in throttling (all-injection concept)

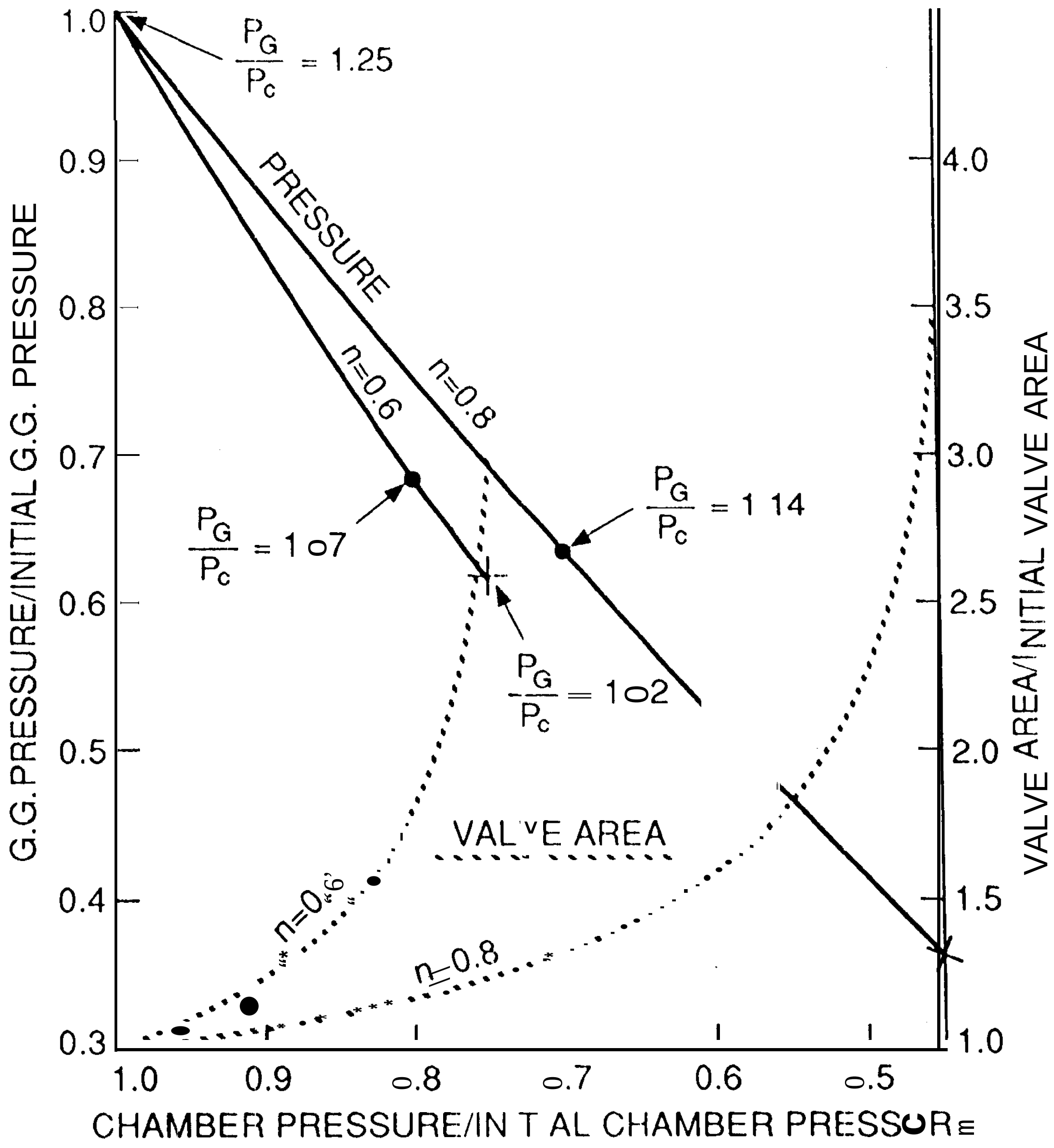

Fig 15 Use of variable control valve area to maintain constant fluid/solid ratio in throttling (neutral grain design, F/S = 0.5)

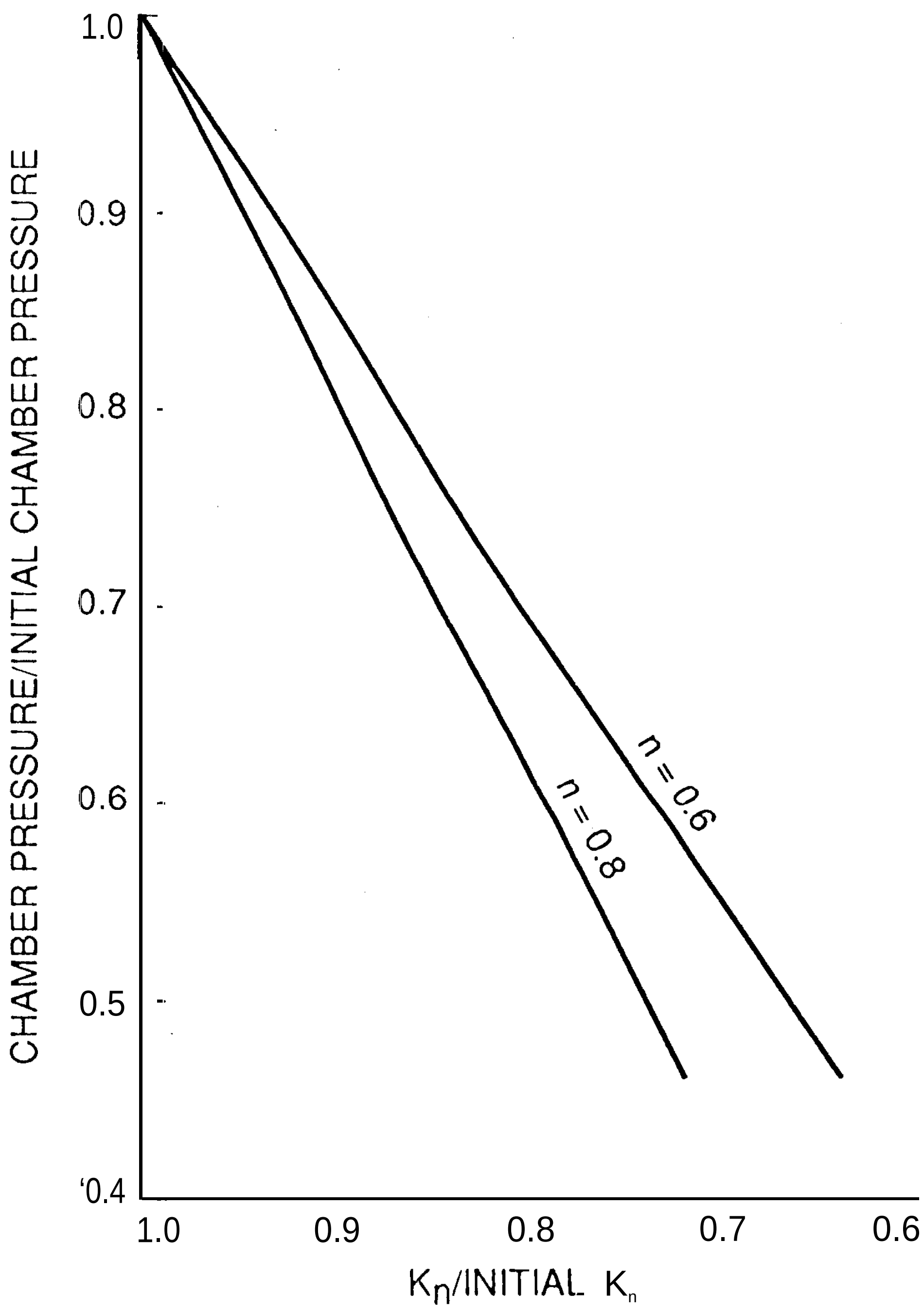

Fig. 16 Regressive grain design schedules to maintain adequate pressure ratio while throttling at contant fluid/solid ratio (F/S = 0.5)

efficient feed of the gas generator gases during the constant mixture ratio throttling.

Fig. 17 shows the gas generator pressure change and valve movements associated with the throttling at constant F/S = 0.5 with the regressive grains. Pressure ratios existing at various places are also indicated. The valve movements are tempered considerably compared with Fig. 15. With $n = 0.8$, only a small vernier-type control is indicated. The increased pressure ratios with decreasing pressure should improve the delivery to the thrust chamber, and without increasing motor weight because the gas generator pressure continues to fall.

Variance in nominal propellant burn rate presents the same considerations for thrust profile and propellant utilization variances as exist with the forward-injection approach, I-he aft-injection concept provides additional flexibility to accommodate the variance because both liquid injection and gas generator flows can be adjusted. A system of sensors working through ballistics softwear to the flow controls would be envisioned.

Thrust Termination Transients

Differential equations analogous to Eq. (9) can be written for the gas generator and for the thrust chamber. The pressure decay in each is computed numerically. While the liquid flow can be stopped rapidly, some care has to be exercised in the speed with which the gas valve is opened because a surge of gas into the thrust chamber could provide a pressure spike.

Results of computations that could be compared to the case of forward-injection (with F/S = 0.5 and $n = 1$) are shown in Fig. 18 for two initial pressure ratios. Also for comparison with forward-injection, the dimensionless time is based on the characteristic time of the gas generator (the characteristic time of the thrust chamber was assumed to be smaller by a factor of 50). The pressure decays shown are those in the thrust chamber. For this case, the valve was assumed to be fully open in one characteristic time and a linear opening function of time was used. The liquid was assumed to be shut off instantaneously. It is observed that the pressure starts to fall rapidly, reflecting the small characteristic time of the thrust chamber. However, the opening of the valve begins to produce a surge into the thrust chamber. The spike that results is larger for the larger pressure ratio. Eventually, the decaying pressures in both chambers prevail and the remainder of the transient is a

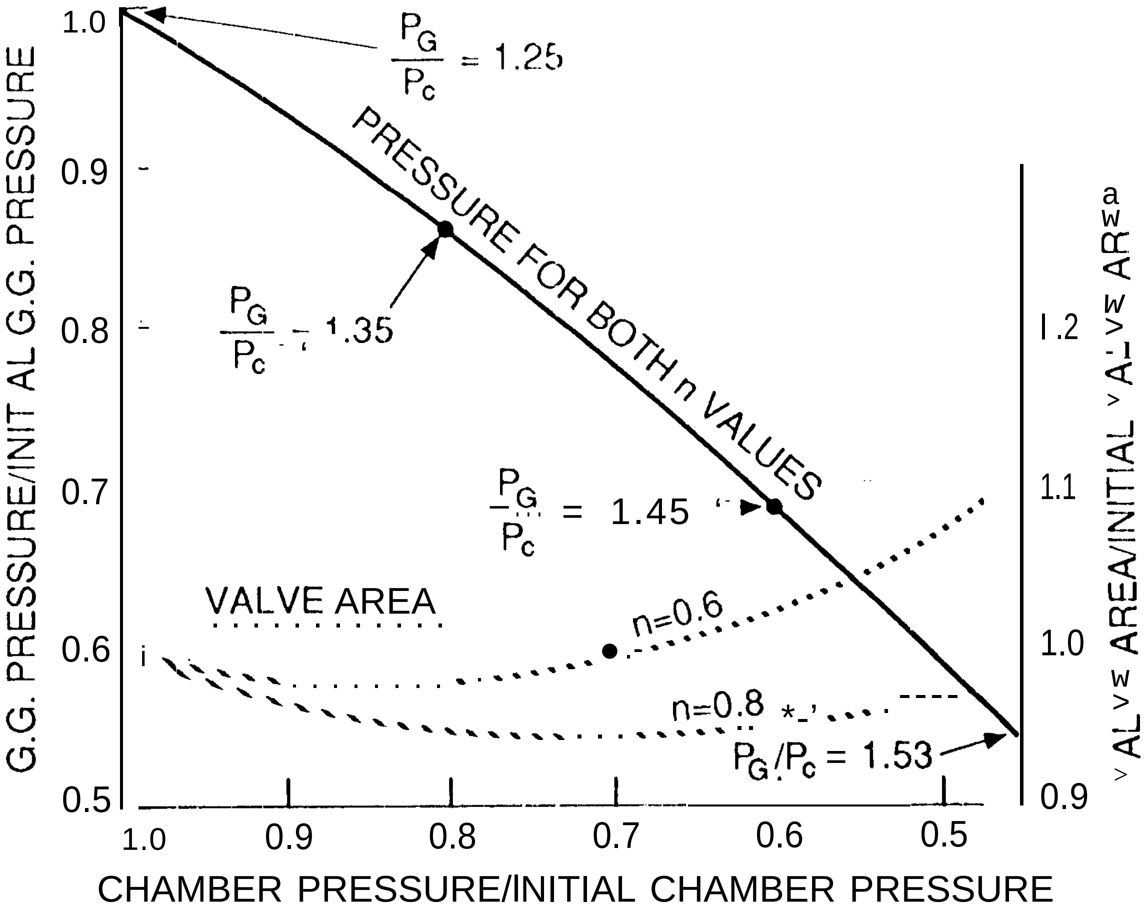

Fig. 17 Use of variable control valve area to maintain constant fluid/solid ratio in throttling (regressive grain design, F/S = 0.5)

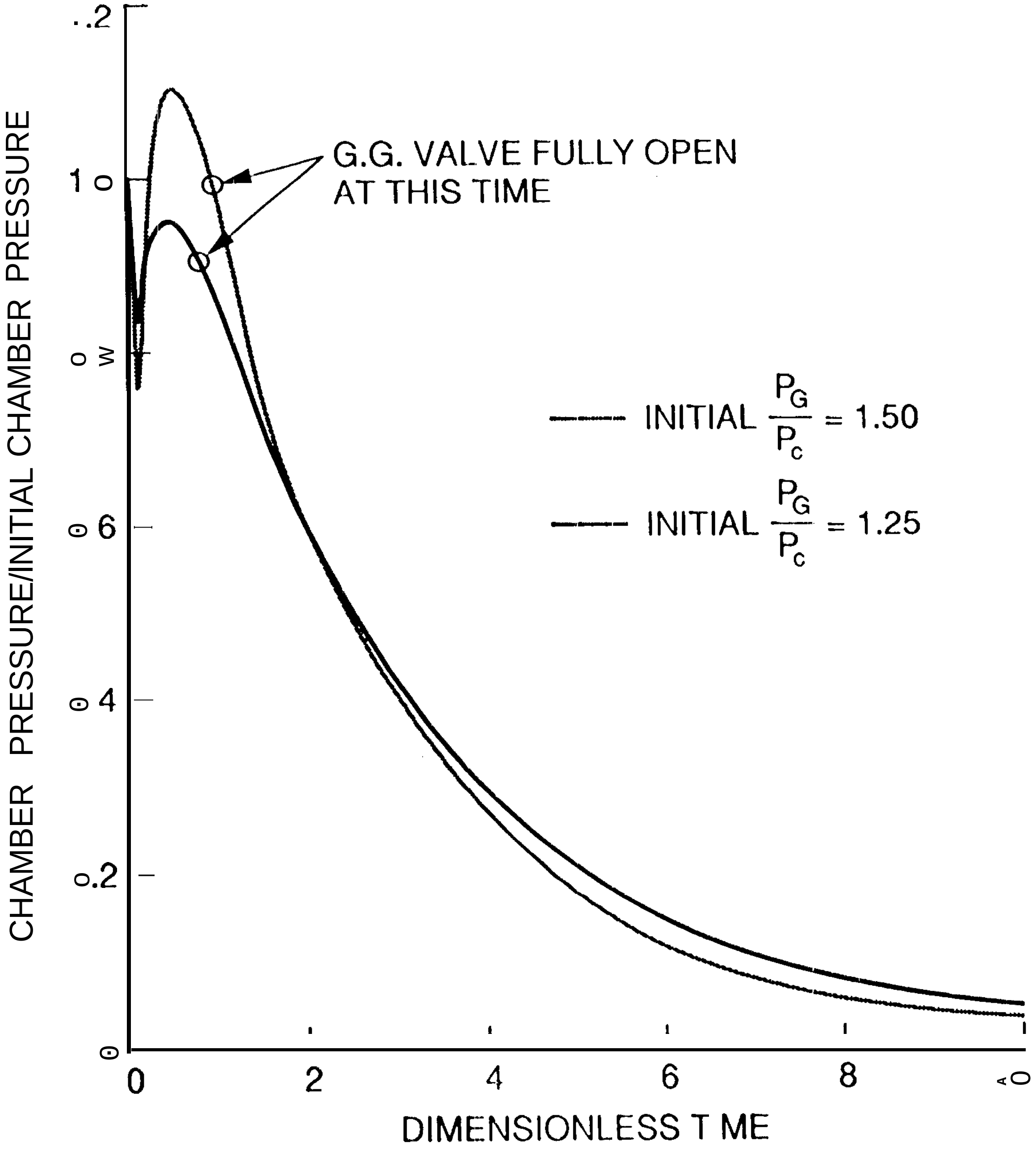

Fig. 8 Effect of pressure ratio on pressure decay following liquid cut-off, valve opens in 1 gas generator characteristic time

smooth decay. By about 10 characteristic times, there is little difference from the result with forward-injection.

The effect of using a longer valve opening time is shown in Fig. 19. Both thrust chamber and gas generator pressure decays are shown here. The higher pressure ratio case is used because that produced the larger spike in Fig, 18. While a spike is not eliminated, its magnitude and brisance are reduced. By 10 characteristic times, the effect of the longer valve opening time is negligible.

An interesting approach that would eliminate the spike and shorten the termination transient would be to incorporate a state-of-the-art valve system to divert much of the gas generator flow away from the thrust chamber and vent overboard in a nulled fashion as part of the thrust termination system. As noted earlier, this dump would also ensure depressurization to ambient pressure for combustion extinguishment.

Stability

Eqs. (14) and (15) were perturbed with respect to burn area numerically, and results were converted into effective pressure exponents for comparison with forward-injection. A baseline n = 1 was used to maintain comparability, and a pressure ratio of 1.25 was assumed. The analogous effective exponents, for comparison with Fig. 5, are shown in Fig. 20. It is seen that fluid injection is not as stabilizing in the aft-injection concept. The reason is that the solid is not as closely coupled to the fluid in this system. However, it is likely that the pressure exponent for aft-injection can be closer to 0.6 than 1.0, especially with the controllability features discussed earlier, so that the effective exponent would be about 0.4. That is comparable to the exponent of the SRM solid propellant.

Feed system stability requires a more complicated analysis with the aft-injection concept. The feed of both the liquid oxygen and the gas generator gases, and two combustion chambers, are involved in the coupling. Analyses of this type for bipropellant liquid engines had only one combustion chamber to contend with.

The set-up for a stability analysis is shown schematically in Fig. 21. The closed-loop feedback systems are illustrated in the form of a thrust chamber outer loop and a gas generator inner loop. Starting at the lower right, a disturbance in the input liquid flow is transformed (through the thrust chamber transfer function) into a disturbance in the nozzle outflow and fed back to the gas generator. The

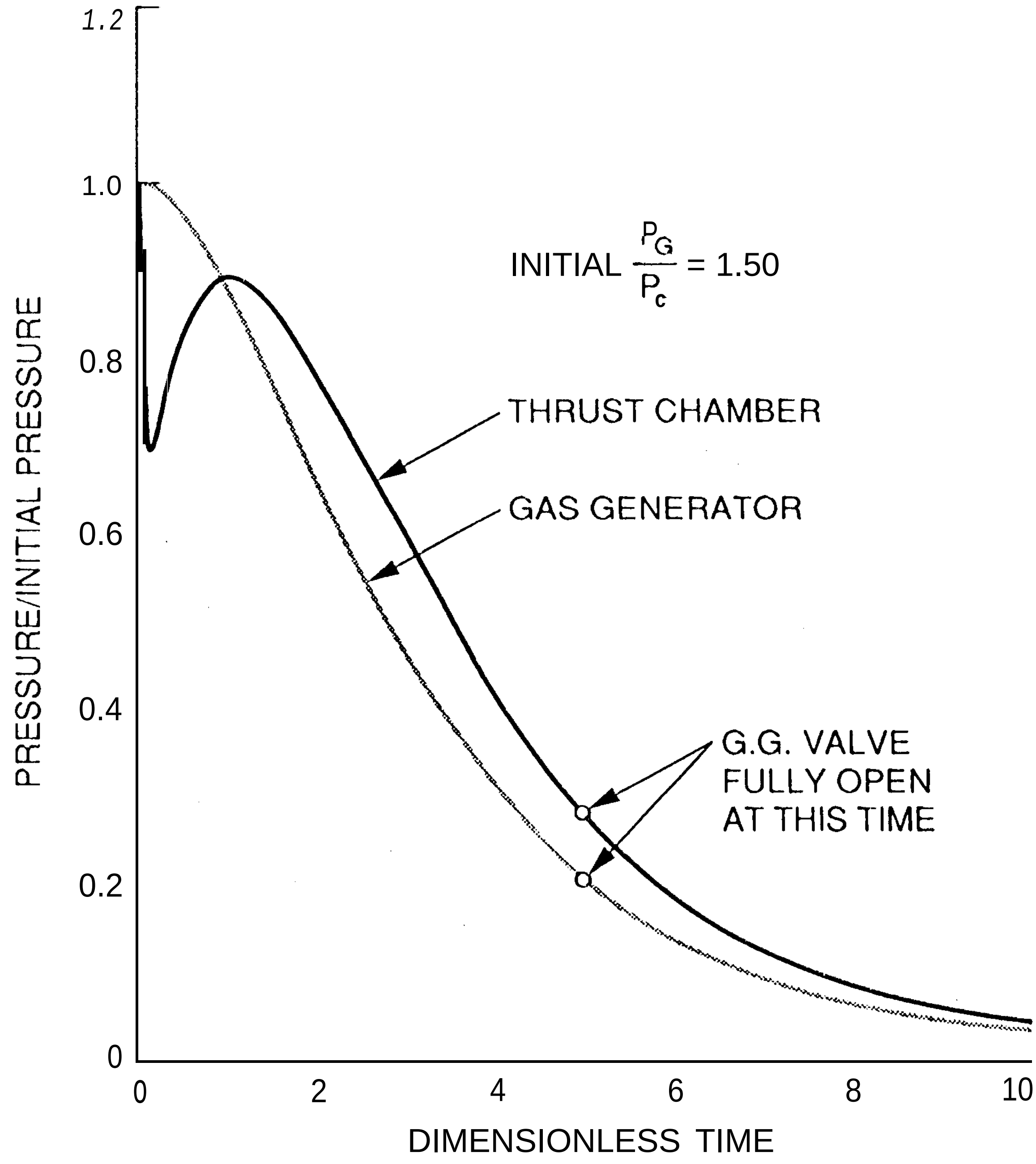

Fig. 19 Effect of valve opening time on pressure decay following liquid cut-off (compare to Fig. 18), valve opens in 5 gas generator characteristic times

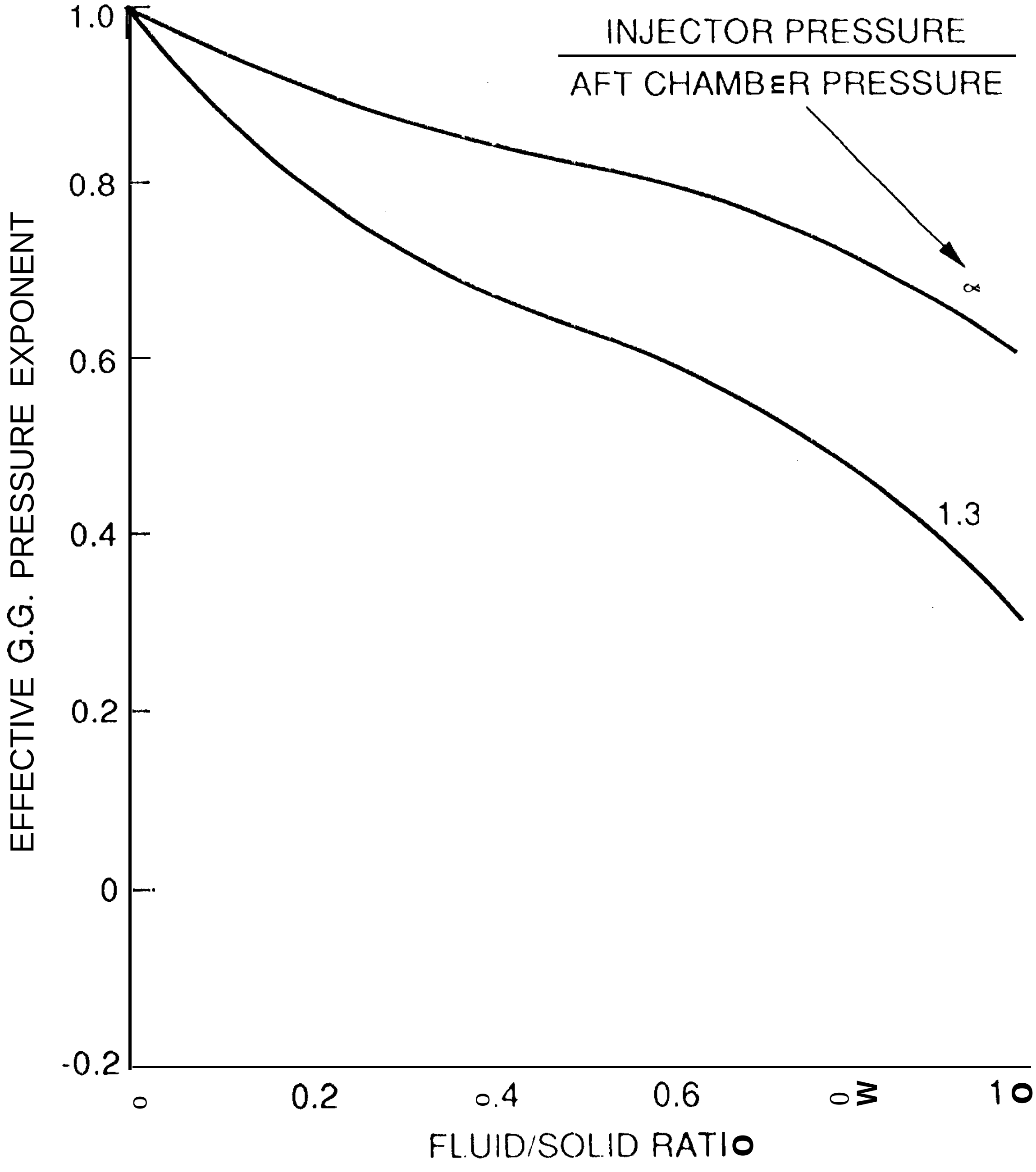

Fig 20 Effective pressure exponent of n = 1 solid propellant with fluid control, using aft-injection concept

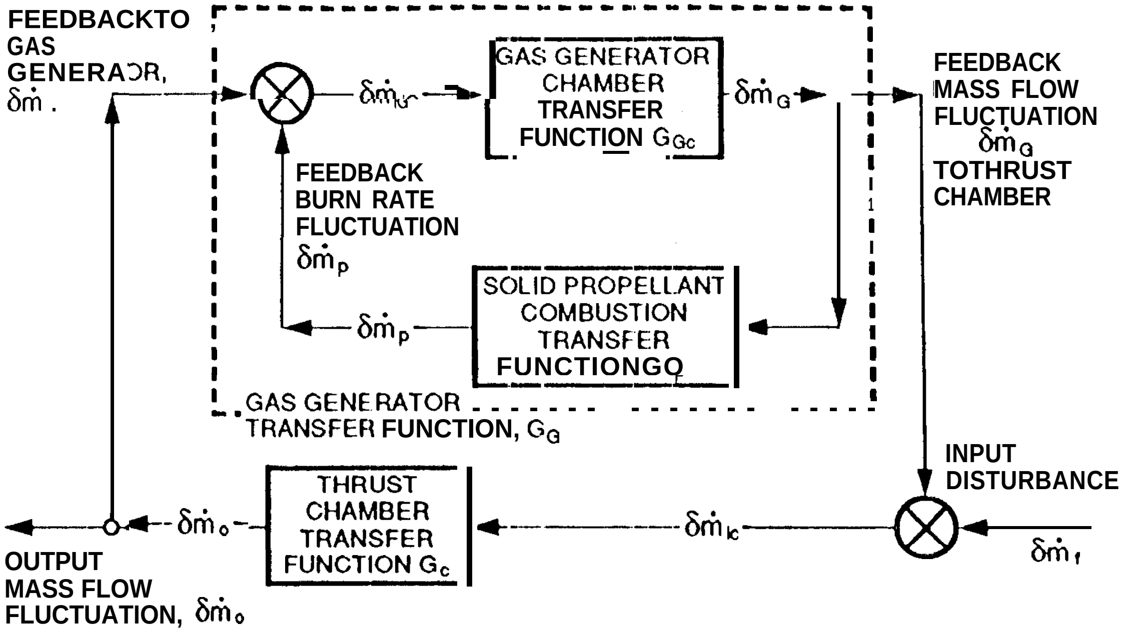

Fig. 2.1 Feedback system for aft-injection hybrid propulsion

feedback is possible because the gas generator operates unchoked. As a result of the gas generator chamber transfer "function, the disturbance is transformed into a pressure fluctuation which is imparted to the propellant combustion zone, The combustion responds to this, through its transfer function (e.g., the combustion response function of combustion instability theory), and feeds back a flow disturbance to the gas generator chamber. That continues in the inner loop, and the flow disturbance in the gas generator chamber is feel back to the source of the input disturbance. For the gas generator feed, the input disturbance would be placed at the upper left.

It is recommended that this type of analysis be carried out in the course of a development program, and used in conjunction with testing. There is concern that injector pressure drops may be pushed too low in the interest of weight savings, especially as regards the gas generator, and system couplings may operate to increase pressurization requirements.

Laboratory Slab Combustor Tests

Purpose

The purpose of these experiments was to integrate the various component technologies in a laboratory-scale demonstration of the fluid-controlled gas generator hybrid concept, confirm that the propellant burns like a solid propellant and not like a solid fuel under fluid control, and observe other characteristics of this type of hybrid combustion. Prior to doing so, the low pressure burn rates and pressure deflagration limit of the gas generator propellant used, Aerojet formulation ANB-3302-4, were measured. It is evident from Figs. 3 and 12 that is it very important to thoroughly characterize the low pressure combustion of the propellant.

Low-Pressure Combustion Characterization Results

The Aerojet gas generator propellant formulation ANB-3302-4, Table 1, was processed at the Jet Propulsion Laboratory.

Table I ANB-3302-4 Formulation

Component	Weight %
Ammonium Perchlorate	61.5
Ammonium Sulfate	16.0
Catalyst	0,5
Hydroxyl-Terminated Polybutadiene (HTPB)	22.0
	100,0?40

1.4 DoD hazard classification

Attempts were made to sustain combustion of propellant samples in the open atmosphere. Larger size samples, 1.3 x 1.3 cm (0.5 x 0.5 in.) and 1.3 x 2.54 cm. (0.5 x 1.0 in.), than normal were used, to reduce heat losses from the combustion zone. 10 Burn rate measurements were made in a Crawford strand burner using 6.4 mm (0.25 in.) diameter propellant strands.

It was not possible to sustain combustion of the propellant at atmospheric pressure. The best that could be achieved was a forced ignition and part-way combustion in the open atmosphere; the sample was ignited with a hot wire and pyrotechnic paste, after which the flame proceeded to shrink and extinguish. In the Crawford bomb the strand self-extinguished immediately following ignition.

Progressive improvements in the combustion in the strand burner were observed with increasing pressure. At 1.4 atm. (20 psia) the strand burned a short distance and extinguished before reaching the start timing wire. At 1.8 atm. the strand burned a longer distance, but extinguished before reaching the stop wire. The first reliable burn rate measurement was achieved at 2.0 atm. (30 psia). On this basis, the deflagration limit was estimated to be 1.9 atm. (28 psia).

Burn rate results are shown in Fig. 22. The drop in burn rate in approaching the deflagration limit is a desirable characteristic, appearing as a very high pressure exponent. At higher pressures the exponent is about 0.6. A development goal might be to increase this exponent value slightly for the aft-injection concept, and more so for forward-injection.

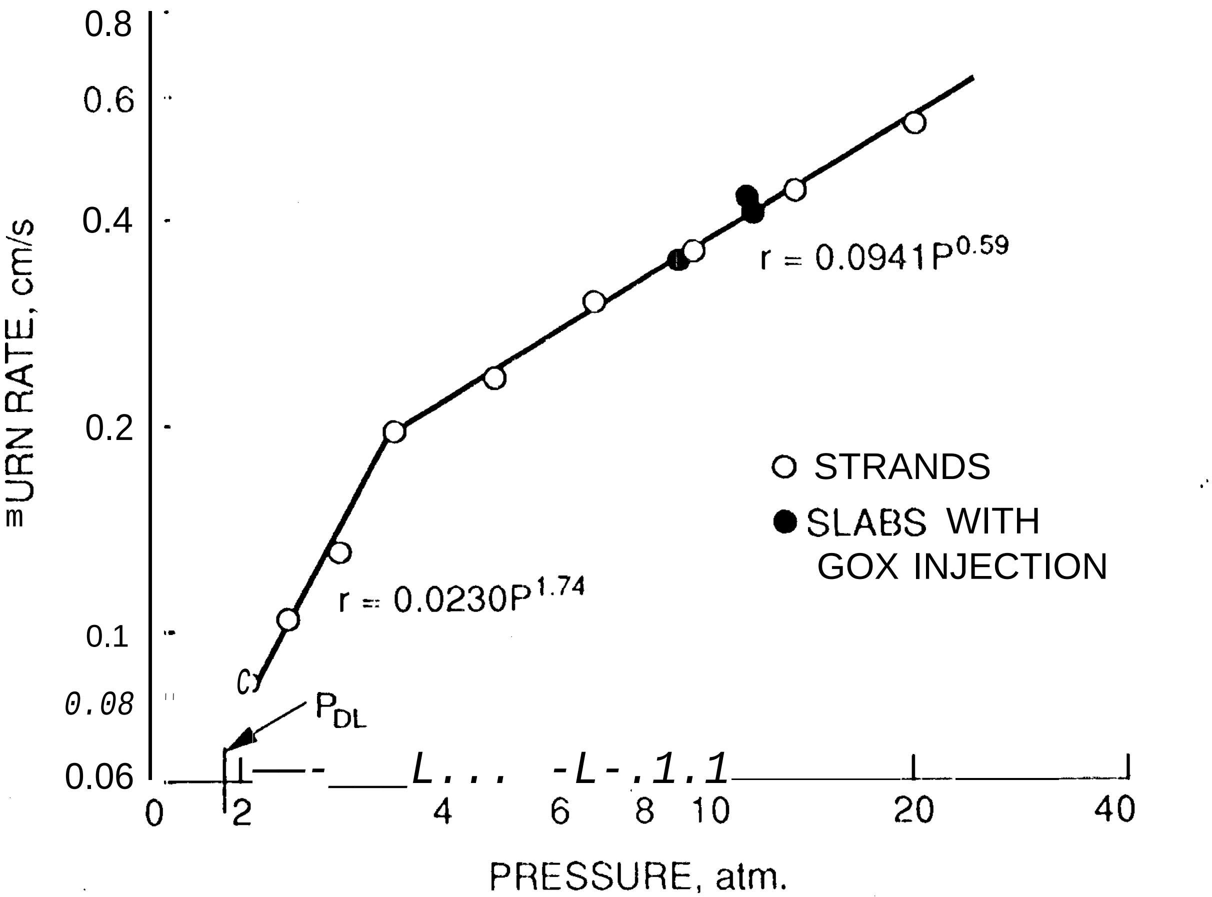

Fig. 22 Low pressure burn rates of Aerojet gas generator propellant formulation ANB-3302-4

Description of Slab Combustor Apparatus

The fluid-control tests were performed using an existing hybrid slab window motor system.[11,12] The motor is shown schematically in Fig. 23. It consists of a (1) head-end closure, (2) flow straightener/igniter section with (3) flow straightening screens, (4) test section with quartz viewing ports, (5) cylindrical aft combustor section, (6) aft closure with (7) graphite nozzle, (8) internal spacer to control burner cross-sectional area, (9) fuel casting base plate, and (10) fuel slab. Ignition of the fuel slab is attained by injecting methane into the oxygen flow in the flow straightener/igniter section and igniting the mixture with dual spark plugs,

For these experiments the fuel slab was replaced with a slab of the gas generator propellant - 6.73 cm (2.65 in.) wide, 20.3 crn (8 in.) long, and 1.27 cm (0.5 in.) thick. The sides were restricted with Halocarbon 25-5S chlorofluorocarbon grease. Gaseous oxygen was injected into the slab combustor either through the head-end port, in the normal fashion, or radially into the aft-combustor section through three sonic orifices spaced around its circumference. There was no attempt to devise a dual chamber apparatus to simulate the actual aft-injection concept. Termination of the slab combustor tests was achieved by terminating the oxygen flow.

Slab Combustor Test Results

Design Precision

The tests were conducted at ambient atmospheric back pressure, Each was terminated after a total burn time of approximately 2 sec., so as not to completely consume the gas generator propellant slab. A noteworthy aspect of the tests turned out to be the precision of their design. Tests were carried out at two design mean pressures, 1.03 MPa (150 psia) and 1.38 MPa (200 psia), and all tests were designed to operate at a fluid/solid ratio of 0.5. Based on integrated oxygen flow rate and slab weight measurements, they operated over the range 0.47 - 0.50. I-he forward-injection test designed for 1,03 MPa pressure exhibited a mean pressure of 0.92 MPa. Forward- and aft-injection tests designed for 1.38 MPa exhibited mean pressures of 1.18 and 1. 19 MPa, respectively (no difference between head-end and aft-end oxygen injection results at the same injection rate). A slightly lower oxygen flow rate compensated for the slightly decreased propellant burn rate (due to the less-than-planned pressure) to maintain the fluid/solid ratio near the planned 0,5 value.

FIGURE 23

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HYBRID SLAB WINDOW MOTOR

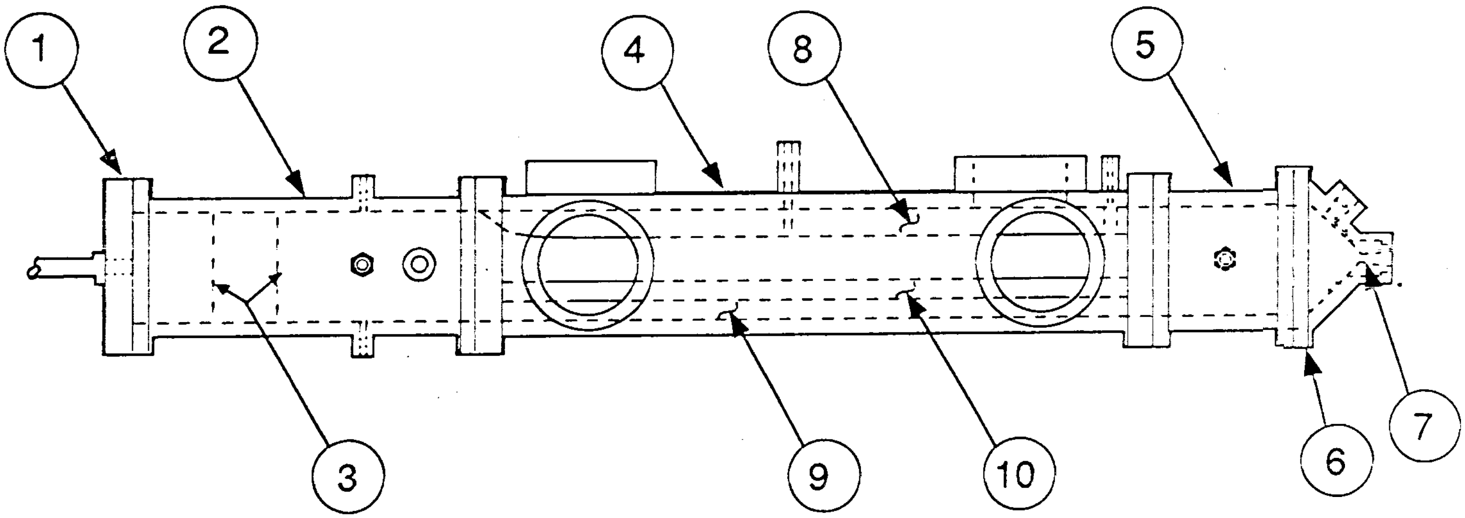


FIG. 24. SLAB COMBUSTOR TEST WITH FORWARD GOX INJECTION

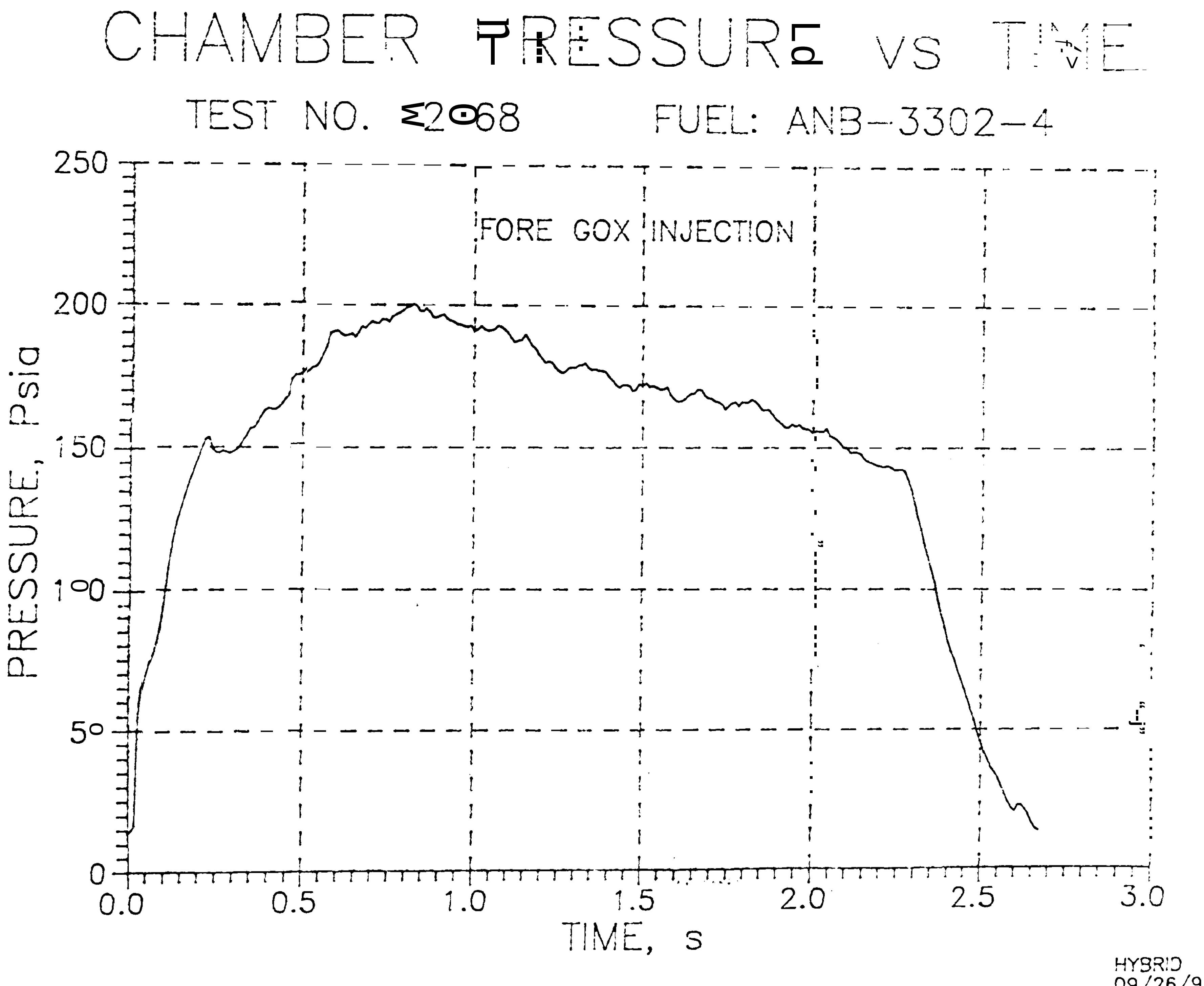
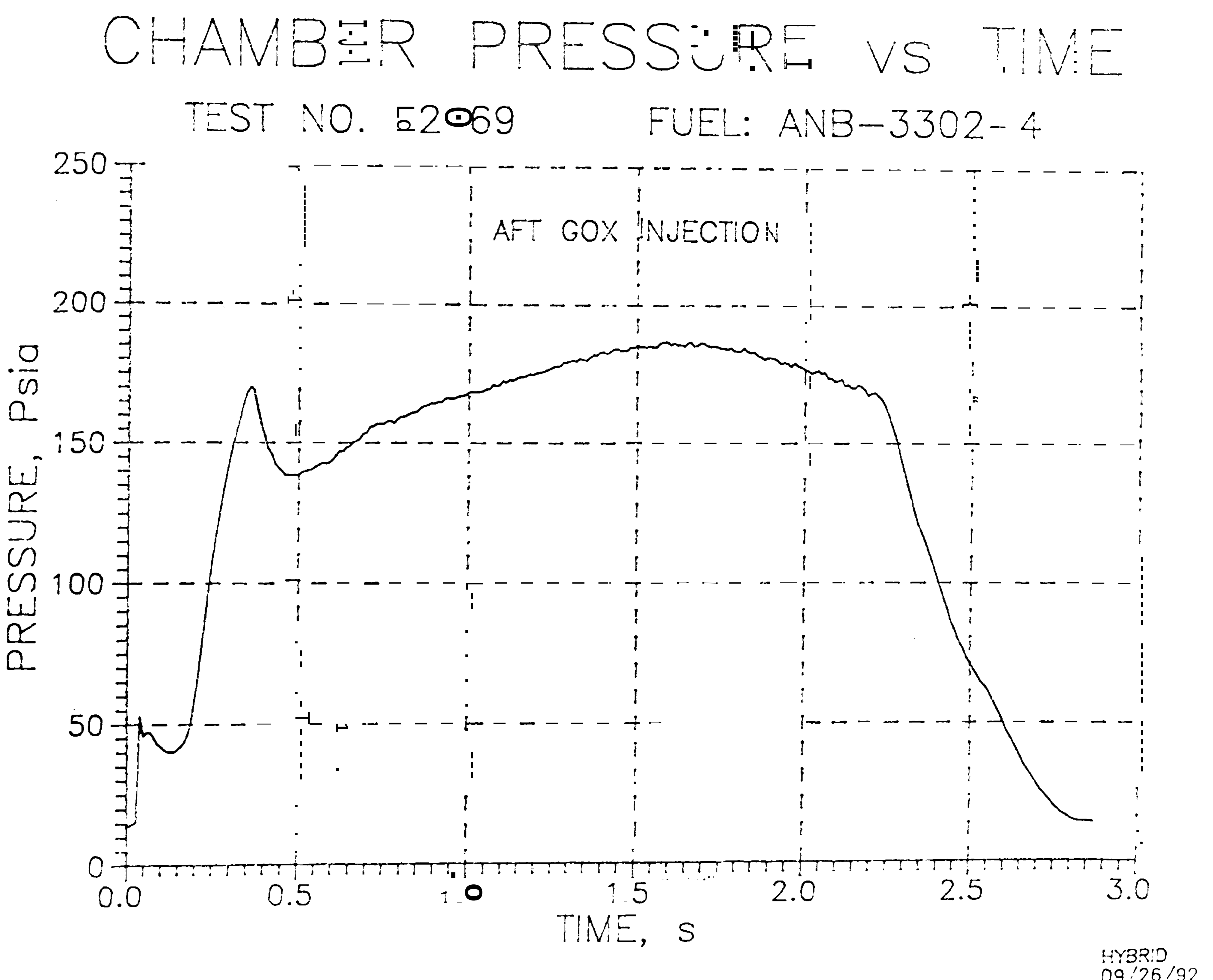


FIG. 25. SLAB COMBUSTOR TEST WITH AFT GOX INJECTION



Extinguishment and Combustion Efficiency

Each propellant slab extinguished successfully upon termination of the oxygen flow. There was no measurable nozzle throat erosion in any test. Approximate c* combustion efficiencies in the 80s were deduced from the test results, at this small scale and low pressures and burn times, with exposed metal walls and with the simplest kind of injection.

Burn Rate Results

Propellant mean burn rates determined from pre- and post-test measurement of the combustor slab thickness are shown on the burning rate-pressure plot in Fig. 22. It is observed that the slabs under fluid control burned at the

same rates as the strands in the strand burner. This agrees with previous results with other types of solid propellants.[7,8]

Stability

Pressure traces for the tests designed for 1.38 MPa pressure are shown in Figs. 24 and 25. Fig, 24 displays the result with head-end injection, Fig. 25 with aft-end. There are two interesting differences in the features of these traces. With head-end injection the trace is regressive in character and shows the same type of irregularity seen in pure hybrid firings with this motor, With aft-injection the trace takes on a progressive character and is smooth.

The differences in trace shape are believed to be attributable to a combination of three factors: (1) more rapid motor filling (pressure build-up) following ignition of the fuel-rich gas generator combustion products-oxygen mixture for the forward-injection configuration, (2) greater effectiveness of the slab restricted grease coating for the lower slab-burner gas temperatures and flow rates with the aft-injection configuration (burning on the sides of the slab produces a regressive K_n-time profile), and (3) time differences in combustion efficiency with this geometric arrangement, As the propellant slab burns for the latter factor, the rectangular port width increases, This is detrimental to efficiency with a simple head-end injection orifice because the mixing in the port becomes less confined. On the other hand, it is beneficial to the aft-injection arrangement (injection radially from side walls into an aft free volume) because the flow of gas generator gases into the aft free volume becomes less centrally directed towards the nozzle and less rapid.

The cliff erence in roughness for the two oxygen injection configurations is significant because it shows that the combustion irregularity is not due to the oxygen feed, or turbulence induced by the step at the aft end of the slabs, or the combustion of the·mixture in the aft-combustor volume. The remaining, actual mechanism for the irregularity observed in the forward-injection test results is speculated to be some type of flow-combustion turbulence interaction along the surface of the propellant slab. However, this interaction does not operate to change the mean burning rate of the propellant,

Conclusions

A hybrid system based upon fluid-controlled solid gas generators is an attractive propulsion alternative. It is verified that the solid gas generator propellant burns like a solid propellant under fluid control, and that it reliably extinguishes at atmospheric pressure. With solid propellant-like ballistic and density properties, a high propellant weight loading is possible.

Two versions of the concept were evaluated: a conventional head-end injection of liquid oxidizer into the solid gas generator motor; and an aft-injection concept whereby products of the gas generator are injected together with the liquid oxidizer into a liquid rocket engine type of thrust chamber.

Advantages of forward-injection are simplicity, stability, and weight savings. A proper design can minimize mixture ratio excursions in throttling and effects of burn rate variances on either the thrust profile or mixture ratio.

Advantages of the aft-end injection concept are a low temperature solid gas generator motor, and a more precise controllability. It has a greater flexibility to throttle at constant mixture ratio and compensate for variances, and the potential for a more rapid thrust termination. Attention will have to be given to adequate pressure ratios in the feed systems in the course of a system development.

The slab combustor tests, taken together with literature data for subscale test motors, indicate that there should be no problem with combustion efficiency with either version in full-scale boosters incorporating efficient injector designs.

Gas generator propellant development to date has been only for the aft-injection version. Some propellant work would be needed to increase pressure exponent to more desirable levels for the forward-injection version.

Acknowledgments

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References

1. "What is the Future of Hybrid Rocket Propulsion for U.S. Space Launch Systems?", A Position Paper by the National Space Propulsion Synergy Group, publication pending.

2, Yaffee, M. L., "Fluid Studied to Modulate Solid Thrust", Aviation Week & Space Technology, Feb. 12, 1968, pp. 65-67.

3. McDonald, A. J., "On-Off and Acceleration Control of Solid Rockets", SAE Paper 710767, Society of Automotive Engineers, National Aeronautics and Space Engineering and Manufacturing Meeting, Los Angeles, Calif., Sept. 1971.

4, Anon., "Innovative Rocket System Combines a Solid and a Gas", CPIA Bulletin, Chemical Propulsion Information Agency, April, 1987; also Aerospace America, AIAA, April, 1988, p.1 (spotlight).

5. Culver, D. W., "Comparison of Forward and Aft injected Hybrid Rocket Boosters", AIAA Paper 91-2586, AIAA/SAE/ASME 27th Joint Propulsion Conference, Sacramento, Calif., June, 1991. (Note - forward-injection as used here refers to a pure hybrid).

6. Culver, D. W. and Mueggenburg, H. H., "Aft Mounted Gas/Liquid Injector Technology for Gas Generator Cycle Hybrid Rockets", AIAA Paper 91-2518, ibid.

7. "Study of Fluid Controlled Solid Propellant Rocket Motors", Report LPC-734F under Contract NAS 7-444, Lockheed Propulsion Company, Redlands, Calif., Aug., 1967.

8. Benin, J.H., Coates, R. L., and Cohen, N.S., "Thrust Magnitude and Restart Control of Solid Motors by injection of Hyperbolic Fluids", J. Spacecraft & Rockets, Vol. 4, March, 1967, pp. 354-358.

9. Coates, R. L., Cohen, N. S., and Harvill, L. R., "An Interpretation of L" Combustion Instability in Terms of Acoustic Combustion Instability Theory, " 3rd ICRPG Combustion Conference, CPIA Publication 139, Vol. 1, Feb., 1967, pp. 291-302.

10, "Propellant Tailoring Techniques for Controllable Rocket Motors", Report LPC-343F, AFRPL-TR-71 -25 under Contract F0461 1 -69-C-0072, Lockheed Propulsion Co., Redlands, Calif., March, 1971.

11, Strand, L.,Ray, R., Anderson, F., and Cohen, N., "Hybrid Rocket Fuel Combustion and Regression Rate Study", AIAAPaper92-3302, AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, Term., July, 1992.

12. Strand, L., Ray, R., and Cohen, N., "Hybrid Combustion Study", AIAA Paper 93-2412, AIAA/ASME/SAE/ASEE 29th Joint Propulsion Conference, Monterey, Calif., June, 1993.